Guidance on Surveys for Subsurface Radiological Contaminants

White Paper

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Prepared for
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) has communicated its desire to extend the “Multi-Agency Site Survey Investigation Manual (MARSSIM)” guidance, which treats only surface surveys, to the subsurface. This white paper summarizes technical efforts focused on assessments of radiologically contaminated subsurface soils.

This white paper reports on national and international survey methods and is intended as an aid in the development of additional guidance for a highly flexible sampling, modeling, and decision analysis approach that emphasizes the quality of decision-making throughout the investigation and state-of-the-art technology. Major challenges face a quality subsurface survey, including lack of clear exposure mechanisms, inaccessibility of the subsurface, lack of comprehensive scans, and increased media complexity. Both onsite and offsite doses are considered.

The white paper also focuses on decision quality and methods that maximize available information, technologies, and expertise to address and mitigate sources of uncertainty through the U.S. Environmental Protection Agency’s Triad methodology. Use of Triad allows the extension of MARSSIM to the subsurface using a substantial and continually advancing set of tools, including spatial analysis, modeling, and the geographic information system (GIS) community. The white paper examines the recommendations made in NUREG/CR-7021, “A Subsurface Decision Model for Supporting Environmental Compliance,” issued January 2012, to develop a spatial variation of the conceptual site model, called the “contamination concern map.” This map focuses on the likelihood of exceeding a decision criterion at a local scale and addresses uncertainty in volume extent and location. The map matures over each major phase of the investigation and provides a decision framework. Results of this approach can inform investigators and regulators alike of a reasonable course of action in the final site assessment.

The white paper also identifies multiple gaps in the data and guidance, ranging from a definition of a hot spot to a lack of computer software capable of performing all desired functions to describe a subsurface volume and related activity uncertainties.

EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) provides guidance for characterization and final status surveys (FSSs) of residual radioactive material at surfaces of soils and structures in NUREG-1575, Revision 1, "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)," issued August 2000 (NRC et al. 2000a),[1] and in NUREG-1757, Volume 2, Revision 1, "Consolidated Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Criteria" (NRC, 2006). NUREG-1757, Volume 2, Revision 2, has been issued as a draft report for comment (NRC 2020c) and is available for use by NRC licensees, although the final version of the guidance document will not be available until sometime in 2022. MARSSIM guidance covers contaminants in surficial materials (i.e., around the top 15 centimeters of soils); subsurface contamination is specifically out of scope. NUREG-1757, Volume 2, Revision 2, references MARSSIM guidance for surficial residual radioactivity but also provides limited guidance on subsurface or buried radioactive material, including dose scenarios that could bring residual radioactivity to the surface. An increasing number of complex decommissioning sites are expected to become active soon. Many of these are reactor sites that can be expected to contain areas of residual radioactivity in subsurface soils. Moreover, instead of entering long-term storage before decommissioning (SAFSTOR), some reactor sites are now being decommissioned soon after shutdown. These facilities will need to be surveyed and a determination made as to the need for subsurface remediation.

The NRC intends to develop guidance for the design and implementation of radiological surveys of the subsurface using statistical methods and risk approaches to determine acceptable numbers and distributions of soil samples (or other subsurface media) taken at depth, to maintain appropriate coverage while keeping costs of sampling and analysis reasonable and minimizing environmental impacts. The guidance would help licensees demonstrate the adequacy of site characterization and the FSS for showing compliance with License Termination Rule (LTR)[2] radiological criteria with reasonable assurance, without being overly conservative. The NRC began to address this problem in NUREG/CR-7021, "A Subsurface Decision Model for Supporting Environmental Compliance," issued January 2012 (NRC 2012), which outlines an approach that overcomes obstacles to detailed subsurface surveys.

The NRC is considering use of MARSSIM-like principles for the characterization and FSS of radioactive contaminants in the subsurface, potentially many meters in depth below ground surface. Material developed in this white paper and input received during public workshops (in July 2021 and May 2022, to date) on the subject areas described below will be used to produce a NUREG/CR report providing the technical bases for guidance on subsurface contaminants. Invitees to the workshops have included experts from remediation companies, academia, national laboratories, and regulatory agencies.

Specific activities being considered by the NRC to develop this guidance include the following:

[1] MARSSIM, Revision 2, has been developed and is expected to be issued for public comment in 2021. An advanced copy is available on the U.S. Environmental Protection Agency's (EPA's) Science Advisory Board Web site: https://yosemite.epa.gov/sab/sabproduct.nsf/RSSRecentAdditionsBOARD/E1D35FEB397932FF8525854D00836CFA.

[2] The LTR went into effect on July 21, 1997, and is contained in Subpart E, "Radiological Criteria for License Termination," of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 20, "Standards for Protection against Radiation."

- Developing guidance to allow a licensee to implement historical, scoping, and characterization analyses and an FSS that are appropriate for evaluating subsurface contamination. The guidance should provide sound decision-making methods, while recognizing the inherent limitations associated with subsurface investigations.

- Developing a statistical approach and methods to determine the necessary sample density, spatial distributions, depths, and volume to achieve a certain level of confidence and limit decision errors for subsurface contaminants during site characterization and especially for the FSS.

- Addressing how subsurface residual radioactivity exposure scenarios differ from those for surface residual radioactivity. For example, given the relative importance of the ground water pathway and intrusion scenarios for subsurface residual radioactivity that involve soil disturbance and mixing, how does the importance of smaller areas of residual radioactivity in the subsurface differ from those at the surface? Integration of dose modeling and radiological surveys is a key aspect of this project.

- Evaluating and implementing the use of geospatial modeling tools and currently available geostatistical software to analyze data and optimize sampling designs. The tools should be able to provide geospatial and statistical evaluation of remediated sites, especially allowing comparison to regulatory criteria. These tools must be able to consider the likelihood of residual radioactivity above levels of concern and uncertainty associated with datasets. New tools may be needed to achieve these objectives.

The work described in this white paper summarizes industry-accepted practices and references for NRC-proposed activities, including historic applications, all focused on subsurface soils. This white paper also provides input on potential changes and issues that would be encountered in applying existing approaches to the subsurface. This document is organized by key topics as discussed below.

SECTION 1—INTRODUCTION

This section captures the intent of the primary international and national standard reference groups and suggested survey design approaches for subsurface soils. This white paper briefly describes key issues concerning contaminants in subsurface soils and how they contrast with surficial MARSSIM-type approaches, and suggests approaches to address survey design, including NUREG/CR-7021, and statistical methods for evaluating contaminants in the subsurface. Section 1 addresses the following:

ISO Standard EN ISO 18557:2020—“Characterization principles for soils, buildings and infrastructures contaminated by radionuclides for remediation purposes.” The International Organization for Standardization (ISO) articulates a set of principles for sampling strategy and characterization of soils, buildings, and infrastructures during nuclear site decommissioning, taking into account constraints imposed by operations, budgets, and regulations while respecting as low as reasonably achievable principles. This ISO document is intended to standardize practices and aid users in planning and reporting characterization activities. Of note for this report, the ISO advocates the integration of geostatistical methods for site characterization. The ISO includes an appendix on geostatistical data processing that elaborates on geostatistical concepts, including analysis of spatial structure, conditional simulation, and multivariate geostatistics to combine distinct sources of information. Remediation of volumetric blocks of soil is discussed. (ISO 2020)

American National Standards Institute (ANSI) Standard ANSI/ANS-2.17-2010—"Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Plants."[3] This standard establishes the requirements for evaluating the occurrence and movement of radionuclides in the subsurface resulting from abnormal radionuclide releases at commercial nuclear power plants. This standard applies to the abnormal radionuclide releases that affect ground water, water supplies derived from ground water, and surface waters affected by subsurface transport, including exposure pathways across the transition zone from ground water to surface water. (ANS 2010)

NUREG/CR-7021—"A Subsurface Decision Model for Supporting Environmental Compliance." This NUREG/CR describes the software Spatial Analysis and Decision Assistance (SADA). It provides a geospatial modeling and decision framework for conducting a subsurface compliance survey and analysis for sites that have been remediated for radioactive contamination. This framework proposes a method to extend the MARSSIM guidance, which treats only surface surveys, into the subsurface. It combines and organizes survey methods into a highly flexible sampling, modeling, and decision analysis approach that emphasizes the quality of decision-making throughout the investigation. (NRC 2012)

Section 1 also summarizes the presentation and discussion at the workshops held to date on the technical bases for subsurface guidance.

SECTION 2—SURVEY APPROACHES FOR DIFFERENT TYPES OF LICENSEES

Compliance assessments for surface and subsurface residual radioactivity have similar objectives; both focus on demonstrating that LTR radiological criteria are met. These criteria consider residual radioactivity (1) averaged over the entire site or survey unit and (2) elevated concentrations in smaller areas of the site or survey unit. However, the subsurface presents substantial challenges that add to the complexity of these surveys. First, access to subsurface soils is limited, and surveying subsurface soils is much more expensive than surveying surface soils. Given limited access to subsurface soils, continuous scanning techniques, which are commonly used to provide fast and detailed surveys of the surface, cannot be used for subsurface soils. Second, subsurface soils can be expected to be heterogeneous in ways that may not be evident. Third, development of derived concentration guideline levels (DCGLs) for subsurface soils is more complex and often involves consideration of various intrusion events that bring subsurface residual radioactivity to the surface, where a receptor could be exposed. In this regard, ground water exposure pathways also appear to be more important for subsurface contaminants than for contaminants found at the surface. For complex sites that operated over extended times, mobile radionuclides may have been transported deep in the vadose zone and into ground water or fractured rock, further adding to the difficulty in characterizing subsurface residual radioactivity. For these reasons, guidance is needed for the design and implementation of radiological surveys of the subsurface with statistical methods to determine acceptable sample distributions in three dimensions. It is hoped that guidance can be developed to demonstrate the adequacy of site characterization and FSSs by providing reasonable assurance of compliance with radiological criteria while limiting overly conservative approaches.

ISO and ANSI standards take into account the regulations covering survey design and summarize the approaches needed for surveys, sampling, and characterization of different types of NRC-licensed sites (e.g., reactors versus materials sites). Section 2 of this white paper

[3] This standard was reaffirmed March 10, 2016.

describes the applicable regulations, such as the LTR and the U.S. Environmental Protection Agency's (EPA's) drinking water standards and ground water protection rules.

NUREG/CR-7268, "User's Manual for RESRAD-OFFSITE Code Version 4," Volume 1, "Methodology and Models Used in RESRAD-OFFSITE Code," issued February 2020 (NRC 2020d), considers three possible subsurface soil configurations. The three primary configurations are (1) the contaminants are above the water table, (2) a portion of the primary contamination is in the water table, and (3) all of the primary contamination is within the water table. Although RESRAD-ONSITE and -OFFSITE are able to simulate a portion of the contaminated zone being in the water table, the codes are unable to address existing ground water contamination outside of the source area, and the contribution to dose of any existing ground water plume must be assessed. NUREG-1757, Volume 2, Revision 2, addresses the remaining subsurface contamination in the vadose zone following decommissioning. This guidance includes consideration of intrusion scenarios that may bring residual radioactivity to the surface, which may complicate the development of cleanup criteria. Also, a review of multiple decommissioning sites in Section 10 of this white paper indicates that multiple DCGLs for multiple depths or environmental media could be employed, which would result in a more complex FSS. A MARSSIM-like survey approach to the three configurations of primary contamination and other intrusion scenarios for residual radioactivity left behind in decommissioning might be applied to the subsurface characterization. The approach includes scoping, characterization, remedial, and compliance surveys. Techniques are presented to calculate the total volume required, if any, for removal (remediation) (NRC 2020d).

The MARSSIM Radiation Survey and Site Investigation process as it relates to the subsurface is examined through the NUREG/CR-7021 perspective, which presents a framework focused on development of a conceptual site model referred to as a "contamination concern map" (CCM). The CCM describes the extent, location, and significance of residual radioactivity relative to the decision criteria. The CCM is developed with the aid of visualization, geographic information systems, and geostatistical software and incorporates information from many different sources and types of input.

SECTION 3—DERIVED CONCENTRATION GUIDELINE LEVELS

Dose modeling is used to determine cleanup levels or DCGLs that meet regulatory criteria for license termination (or to demonstrate compliance with LTR criteria based on measurement of final residual radioactivity levels). After remediation has been completed, an FSS needs to be conducted to confirm that residual radioactivity remaining at the site meets the LTR radiological criteria. While procedures for these surveys and the statistical approaches used for their analysis have been available for surficial contamination in MARSSIM, the NRC is considering formulating guidance on these procedures for subsurface contamination.

The following points should be considered in relation to the development of DCGLs for the subsurface:

- Limited guidance is available on distinguishing between the surface $DCGL_W$ (wide area) and a subsurface DCGL (see NUREG-1757, Volume 2, Revision 2, Section 3.6, Appendices G, I, and J).

- A surface MARSSIM-based approach may be extended to subsurface planes such as excavation surfaces (see NUREG-1757, Volume 2, Revision 2, Appendix G). Different classes of survey units may apply to the surface of the excavation versus the walls of the excavation or surface soils.

- Multiple DCGLs may be useful depending on the radionuclides present, applicable exposure scenarios, and actual site conditions. It is always acceptable to use the most limiting DCGL; however, in certain cases (e.g., deep subsurface residual radioactivity), it may be beneficial to develop separate DCGLs, because of the importance of the ground water pathway versus surface dose pathways. Multiple DCGLs add complexity to the FSS, which may be an important consideration in the FSS design. Using multiple DCGLs may be more straightforward in cases where different sources are present (e.g., residual radioactivity at the surface versus residual radioactivity associated with buried material or from deep subsurface spills or leaks that may contain mixtures of radionuclides).

- For buried residual radioactivity, most cases will require consideration of potential intrusion scenarios that could bring deep subsurface contamination to the surface, as well as "as is" conditions for residual radioactivity remaining after the intrusion event.

- The MARSSIM application of a "survey unit" may not directly apply to the subsurface.

- A higher level of analytical sensitivity is required for sites with greater numbers of significant radionuclides, which affects statistical testing considerations.

NUREG-1757, Volume 2, Revision 2, presents several scenarios for buried materials, including the following:

- basement excavation (residual radioactivity within 3 meters of the surface considering erosion) and other scenarios if residual radioactivity is found deeper in the subsurface (e.g., well drilling)

- large backfilled subgrade structures (e.g., containment basements, auxiliary building basements, and/or turbine basements at a reactor site), including large-scale excavations

This section of the white paper also summarizes NRC-acceptable computer codes for developing DCGLs.

SECTION 4—IMPLICATIONS OF NUREG-1757, VOLUME 2, REVISION 2

This section explores the importance of (1) the effect of distance between a contaminated layer and the water table on dose, (2) approaches to subsurface assessments, (3) categorization and classification of subsurface soils, and (4) the importance of smaller areas of residual radioactivity in the subsurface. The following are major points in the discussion of subsurface soil in Section 4:

- For surface sources, the dose from the water-independent and water-dependent pathways typically occurs at different times. The contribution from water-dependent pathways can be delayed until radionuclides transported by ground water reach a point of water withdrawal (i.e., a well or pond).

- The concentration in ground water generally decreases the farther away it is from its source because of dispersion and may decrease because of dilution following extraction from a well as the result of mixing with clean water.

- NUREG-1757, Volume 2, Revision 2, provides hypothetical examples of intrusion into a buried fill or excavation of a contaminated layer below the surface and how, once the material is brought to the surface, the RESRAD-ONSITE software can be used to determine DCGLs through dose modeling.

- The concept of a highly contaminated small subsurface volume and its impact on the water-dependent pathway is not easily defined. The size of a hypothetical subsurface “hot spot” volume that is applicable to all licensees is also not identified. This analysis is site specific but remains ambiguous, as an instrument scan cannot be performed to determine how big such a hot spot might be and the impact on dose per radionuclide. Instead, information from historical and scoping surveys, professional judgment, geostatistical tools, and dose modeling can be used to determine the volumetric extent and impact of the hot spot, as summarized in Sections 6–8 of this Executive Summary and in the main body of the white paper.

SECTION 5—STAGES OF THE SUBSURFACE DECISION FRAMEWORK

This section discusses methods and considerations for performing various types of subsurface radiological surveys ranging from historical site assessments, scoping, characterization, remedial action, confirmatory, and FSSs. Figure ES-1 shows the general flow of the subsurface decision framework, which is similar to the MARSSIM framework. The different phases depict how the subsurface analysis moves from a very qualitative beginning to a more quantitative conclusion through a series of phases that are identified in the MARSSIM guidance. Each oval represents a major phase in the investigation. These phases are broadly defined to permit the flexibility needed to deal with varying situations. Each arrow shows a potential path through the framework and is annotated by the output content from the previous phase. In turn, this output becomes the input for the next phase. The major theme is to use the historical site assessment to create an initial CCM. Then, the output of each major phase (which serves as input in the next phase) includes the latest CCM update as well as other relevant products. The end result is success in the compliance phase or a return to an interim phase under compliance failure. The framework suggests some methods that may be useful in compliance phase activities (NRC 2012, page 13).

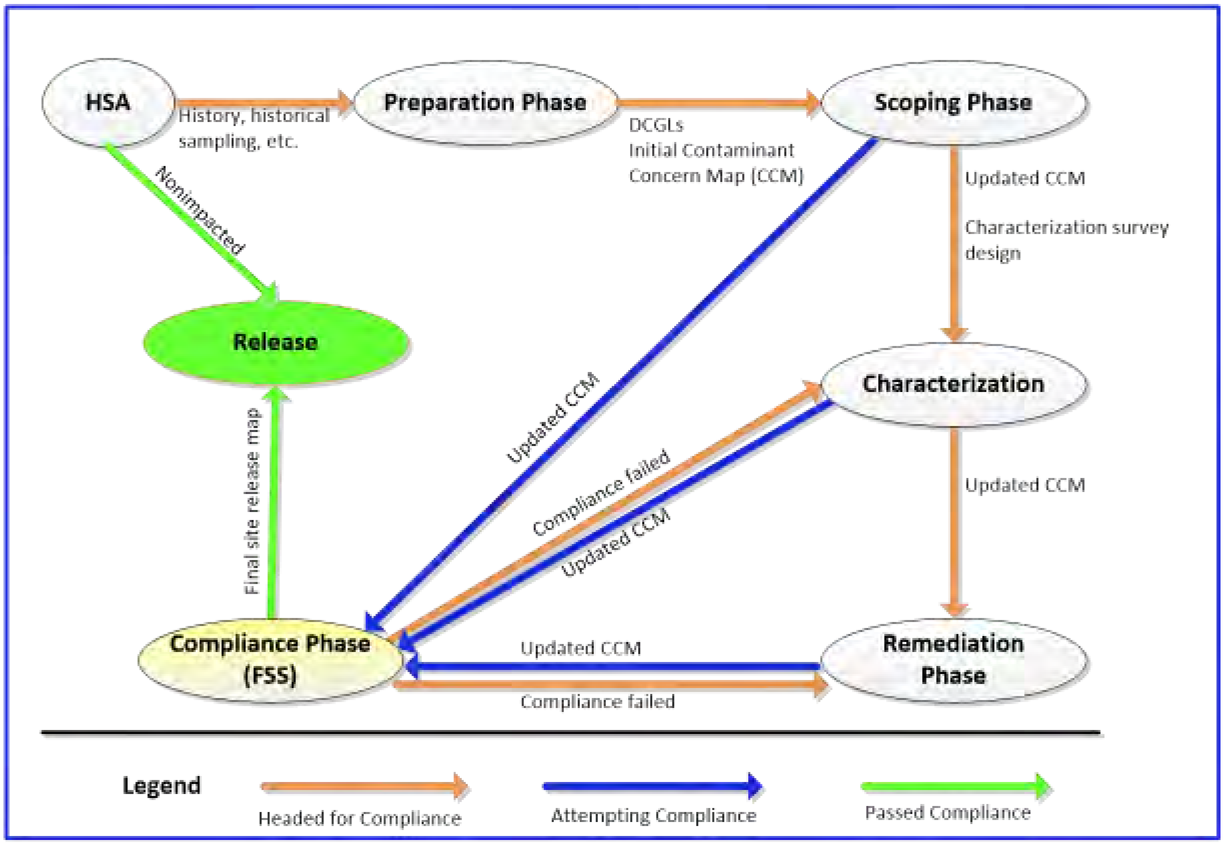

Figure ES-1 Flow Diagram for the Performance-Based Subsurface Compliance Framework

Source: Updated from NUREG/CR-7021, page 13 (NRC 2012)

SECTION 6—GEOSPATIAL MODELING TOOLS

This section describes and evaluates geospatial modeling tools and currently available geostatistical software to analyze data on contaminant distributions and optimize sampling, scanning, or otherwise obtaining information on the subsurface. These tools must be able to consider the likelihood of residual radioactivity above levels of concern and uncertainty associated with a dataset.

The EURATOM work program INSIDER (Improved Nuclear SIte characterization for waste minimization in Decommissioning under constrained EnviRonment) launched in June 2017 (https://insider-h2020.sckcen.be/) (EURATOM 2017). The program proposes a strategy for data analysis and sampling design for initial nuclear site characterization based on a statistical approach. It examines several approaches for using geostatistics to aid sample design, especially for secondary sample designs using data from prior surveys.

There are many geospatial modeling tools. The Electric Power Research Institute sponsored the report "Guidance for Using Geostatistics to Develop Site Final Status Survey Program for Plant Decommissioning" (EPRI 2016). The report extensively evaluated 17 two-dimensional (2D) and three-dimensional (3D) software packages for cost, dimensionality, directed workflow, exploratory data analysis, sample design/optimization, point kriging, block kriging, universal kriging, co-kriging, spatial-temporal kriging, discontinuities or complex geometries, conditional simulation, cross validation, fate and transport modeling, dose assessment, and graphical information system. Of the 3D software packages, SADA is recommended in this white paper because of its use in CCMs, sampling optimization, and remediation cost-benefit analysis, and because it is free. VSP (Visual Sample Plan) is another excellent sampling design and data analysis program, also freeware, but it is a 2D package. The EPRI publication extensively reviews both SADA and VSP.

Examples of the types of problems SADA can address include the following:

- calculating the volume or area of contamination above a cleanup threshold and presenting a site map with a map of contamination above a cleanup threshold on top of the site map

- calculating the area or volume requiring cleanup as a function of cleanup level and generating costs for remediation to the different cleanup levels

- selecting optimal sampling locations and placing them on a site map

The SADA software provides *informed* initial design strategies, where the CCM is used to assist in survey design along with the “Check and Cover” strategy (Stewart et al. 2009). As described in NUREG/CR-7021, this sample design seeks to check those locations where contamination is more likely to exist, while at the same time providing some coverage to low-probability areas. Unfortunately, the module to perform the function of “Check and Cover” is not available. A major issue with SADA is that it is not currently supported or maintained, nor has the code been subject to verification and validation studies. It is recommended that the NRC investigate the level of effort and how SADA, or components of SADA, can be used either stand-alone, or in conjunction with other software, such as VSP. Sections 7 and 8 further address SADA and VSP.

SECTION 7—STATISTICAL METHODS AND TESTS

This section presents statistical methods to determine the necessary sample density, spatial distributions, depths, and volume to achieve a certain level of confidence and limit decision errors for subsurface contaminants during characterization surveys. The MARSSIM statistical tests are evaluated for applicability, and alternative methods are proposed. Key points of the section include the following:

- Because sampling the subsurface is costly, the design of subsurface surveys should include some measure of the value added to the decision-making process for each additional location sampled. The number of samples should be based on a metric that changes as the sample size increases. Therefore, a measure like the statistical power in MARSSIM is desirable. Such a measure is also important to evaluate the adequacy of an FSS.

- The most promising methods for designing efficient subsurface surveys appear to be Bayesian Ellipgrid (geometrical) and Markov-Bayes (geostatistical). Both of these methods are implemented in SADA.

- The Historical Site Assessment can provide the prior information needed to use the Bayesian tools, and thus should be as complete and accurate as possible.

- No single software package provides all the tools that would be desirable for subsurface sampling design and data analysis.

- VSP and SADA appear to have the set of features that may be most useful for Radiological Site Surveys and Investigations, although ProUCL also contains useful features. VSP is supported, maintained, and updated periodically with new features. SADA is available to download, but not currently supported, maintained, or updated.

- It may not be fruitful to spend a great amount of effort in calculating and fitting variograms.

SECTION 8—GEOSPATIAL AND STATISTICAL METHODS

This section reports on the use of geospatial and statistical methods to evaluate remediated sites, especially allowing comparison to regulatory criteria. The section also examines the applicability of MARSSIM statistical tests and possible alternative methods, as appropriate. This includes analysis software that might be used to support a release decision for a subsurface survey unit. This involves the data quality objectives process and limiting decision error rates.

In reviewing available geostatistical software for subsurface FSSs, Section 7 of this report narrowed the recommendations to SADA and VSP. Appendix E to this white paper lists the survey designs in VSP and SADA. The features of these programs are compared:

- The data quality objective process is briefly discussed with comments on application to subsurface sampling design, and decision rules.

- The geostatistical tools in both SADA and VSP are based on the FORTRAN code in Geostatistical Software Library (GSLIB).

- VSP supports more classical statistical methods, although it also contains geostatistical methods outside of the MARSSIM module.

- SADA supports more geostatistical methods than classical methods.

- Guidance is needed to define a subsurface survey unit (SSU) or subsurface volume.

This white paper recommends that either VSP or SADA be upgraded to include 3D modules, especially for “Check and Cover.”

SECTION 9—ASSESSING BACKGROUND AND SCENARIO B

This section evaluates the challenges associated with assessing background radionuclide concentrations and disaggregating background radioactivity from residual activity from licensed activities. This section also discusses the applicability of Scenario B[4] for subsurface residual radioactivity and practical approaches for demonstrating indistinguishability from background.

[4] Licensees must determine whether Scenario A or Scenario B will be used to evaluate the survey unit. Scenario A uses a null hypothesis that assumes the concentration of radioactive material in the survey unit exceeds the $DCGL_W$. Scenario A is sometimes referred to as “presumed not to comply” or “presumed not clean.” Scenario B uses a null hypothesis that assumes the level of concentration of radioactive material in the survey unit is less than or equal to the

The use of Scenario B is expected only for a small number of facilities, and the considerations for any given facility are expected to be site specific. NUREG-1505, Revision 1, “A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys—Interim Draft Report for Comment and Use,” issued June 1998 (NRC 1998a), provides an example of the use of Scenario B to demonstrate indistinguishability from background when the residual radioactivity consists of radionuclides that appear in background, and the variability of the background is relatively high. In a revision to Appendix G to NUREG-1757, Volume 2, the NRC indicates that Scenario B might be used if there is uncertainty as to backfill soils being impacted (NRC 2020c). Appendix G to NUREG-1757, Volume 2, Revision 2, contains additional information, including 3D data, and other examples for surveys involving Scenario B (NRC 2020c).

SADA does not implement Scenario B (Stewart et al. 2009), although VSP does. VSP is also able to produce retrospective (and prospective power curves) for Scenario B evaluations, which are essential to ensuring that a dirty site is not released due to insufficient power to reject the null hypothesis in Scenario B. Additional features related to Scenario B are currently (fiscal year 2021) being addressed under an NRC contract with Pacific Northwest National Laboratory.

SECTION 10—EVALUATIONS OF LARGE SOIL EXCAVATIONS AND EQUIPMENT

This section describes and evaluates methods to survey large subsurface soil excavations and to survey soils for reuse in large excavations including use of conveyor belts and other soil sorters. Key points identified in this section include the following:

- This section describes how a conveyorized survey machine is used and what soil sorters are available.
- A surface $DCGL_W$ (wide area) has been applied to excavation sides and bottoms in several instances. This section reviews how several sites (including nuclear power plants) developed and implemented DCGLs.
- This white paper suggests that SADA could be used to increase confidence that licensees are correctly identifying all areas that need to be remediated. Only the NRC has actually applied SADA in a site review; the guidance and tools for the industry are yet to be developed.

While multiple lessons can be learned from several sites as summarized in the white paper, excavation experiences across the industry are inconsistent in handling layers and volumes just above the DCGL. Lessons learned include topics for dose modeling, characterization, and remediation. A topical MARSSIM-like roadmap for all licensees needs to be developed to illustrate when remediation is necessary.

SECTION 11—AUTONOMOUS VEHICLES SCANNING METHODS AND TECHNIQUES

This section considers the use of autonomous ground vehicles (AGVs) to perform scanning surveys. Such equipment could potentially be useful for slopes and benches in excavations or deep subsurface surveys over relatively smooth terrain. AGVs could be used in conditions that would otherwise pose dangers to workers performing a walkover scan. In addition, AGV

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action level or lower boundary of the grey region. Scenario B is sometimes referred to as “indistinguishable from background” or “presumed clean.”

surveys offer improved survey design and quality over walkover surveys in that the former can attain a near-constant survey speed, thereby better controlling time intervals over a specified area. AGV surveys also result in lower uncertainty related to average detector survey heights as they eliminate the height changes caused by the pendulum-like swinging of the detector during walkovers. As uncertainty regarding survey height and speed is also better controlled than that with a walkover scan, measurement quality objectives can be better defined.

A limited number of autonomous radiological survey platforms are currently available that can be used to conduct radiological site characterization, assist with remediation efforts, or conduct site clearance in accordance with MARSSIM. These systems include inorganic scintillators, light detection and ranging, global positioning, inertial guidance, wireless telemetry, and signal processing systems. They work with various types of vehicles, from small battery-powered vehicles capable of carrying one detector to small tractors and skid steers with pull behind wagons capable of carrying multiple detectors for larger scan paths. Some include the option to identify isotopes through regions of interest and to set a constant speed to meet survey design and measurement quality objectives. This section describes three example platforms.

SECTION 12—TREATMENT OF UNCERTAINTY AND DATA SUFFICIENCY

This section provides methods of treating uncertainty and data sufficiency.

The statistically rigorous quantitative application of measurement quality objectives plays a central role in the process described in the “Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME)” (NRC 2009a). Measurement quality objectives did not appear explicitly in MARSSIM, Revision 1 (NRC 2000a), but were subsequently developed for radioanalytical chemistry measurements as part of the “Multi-Agency Radiological Laboratory Analytical Protocols Manual” (MARLAP), issued July 2004 (NRC 2004). However, these concepts apply equally well to field measurements of radiation and radioactivity. The MARSAME process incorporates these ideas and extends them to these measurements.

A major development since the initial publication of MARSSIM was the 1995 release of the *Guide to the Expression of Uncertainty in Measurement*, or “GUM” (ISO 1995). The procedures described in the GUM have become a de facto standard for estimating the uncertainty associated with measurements of any type. The GUM methodology is essential for the assessment of measurement uncertainty but was not previously treated in MARSSIM.

MARLAP recommends that all radioanalytical laboratories adopt the terminology and methods of the GUM (ISO 1995) for evaluating and reporting measurement uncertainty. The laboratory should report all results, whether positive, negative, or zero, as obtained, together with their uncertainties. This section provides an example of determining uncertainty with the free software GUMCalc, which is user friendly and eliminates the high-level math calculations for field applications. Other available software programs include the National Institute of Standards and Technology Uncertainty Machine and GUM Workbench Version 1.4. This white paper recommends extending MARLAP recommendations to apply to the determination of uncertainty of subsurface sample measurements, whether laboratory or field instrument measurements. Guidance may be developed from the material presented in the white paper.

SECTION 13—ELEVATED AREAS AND HOT SPOTS

This section describes approaches to evaluating elevated areas or hot spots for potential doses to receptors, including the inadvertent intruder. An area of elevated activity is often referred to as a “hot spot.” This term was purposefully omitted from MARSSIM because it often has different meanings based on operational or local program concerns. As a result, the MARSSIM authors decided that problems may be associated with defining the term and reeducating MARSSIM users in its proper use. Because these implications are inconsistent with MARSSIM concepts, MARSSIM does not use the term (NRC 2000a).

NUREG/CR-7021 provides a geospatial modeling and decision framework for conducting a subsurface compliance survey and analysis for sites that have been remediated for radioactive contamination. The framework presented above proposes a method to extend the MARSSIM guidance into the subsurface. It combines and organizes survey methods into a highly flexible sampling, modeling, and decision analysis approach that emphasizes the quality of decision-making throughout the investigation. NUREG/CR-7021 acknowledges the extraordinary costs associated with intense sampling and, in lieu of complete subsurface removal, responds by focusing on the quality of the final compliance decision and the reasonable mitigation of uncertainty (NRC 2012). This white paper explores combining the use of EPA traditional searches for hot spots and the use of geospatial modeling.

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ACRONYMS

ADAMS	Agencywide Documents Access and Management System
AL	action level
ALARA	as low as reasonably achievable
ANL	Argonne National Laboratory
ANS	American Nuclear Society
ANSI	American National Standards Institute
AOC	area of concern
BNL	Brookhaven National Laboratory
Bq/kg	becquerels per kilogram
CCM	contaminant concern map
CFR	*Code of Federal Regulations*
cm	centimeter
CSM	conceptual site model
DandD	decontamination and decommissioning software
DCGL	derived concentration guideline level
$DCGL_{EMC}$	derived concentration guideline level for elevated measurement comparison
DCGLv	derived concentration guideline level designed for subsurface soil volumes
$DCGL_{W}$	derived concentration guideline level designed for wide-area surface soil
DL	discrimination limit
DOE	U.S. Department of Energy
DQO	data quality objective
DP	decommissioning plan
EMC	elevated measurement comparison
EPA	U.S. Environmental Protection Agency
FGR	Federal Guidance Report
FIU	Florida International University
FSS	final status survey
FSSR	final status survey report
GIS	geographic information system
GTF	Groundwater Task Force (NRC)
GM	Geiger-Mueller
GMS	statistical tools software
GPR	ground penetrating radar
GPS	global positioning system
GUM	*Guide to the Expression of Uncertainty in Measurement* (ISO document)
H_0	null hypothesis
HSA	historical site assessment
HTD	hard-to-detect
ICET	Institute for Clean Energy Technology (Mississippi State University)
IL_{PP}	investigation level *a posteriori* for postprocessed data
INSIDER	Improved Nuclear Site Characterization for Waste Minimization in Decommissioning under Constrained Environment (software program)
ISO	International Organization for Standardization
ISOCS	In Situ Object Counting System
ICRP	International Commission on Radiological Protection
keV	kiloelectron volt
L	liter
LACBWR	La Crosse Boiling-Water Reactor
LBGR	lower boundary of the gray region

LTP	license termination plan
LTR	License Termination Rule
m	meter
MARLAP	Multi-Agency Radiological Laboratory Analytical Protocols Manual
MARSAME	Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MCL	maximum contaminant level
MDC	minimum detectable concentration
MDCR	minimum detectable count rate
MeV	megaelectron volt
Micro*Shield*	gamma dose modeling software by Grove Engineering
MCNP	Monte Carlo N-Particle Transport Code
MOU	memorandum of understanding
MQO	measurement quality objective
mrem	millirem
mSv	millisievert
NaI	sodium iodide
NARM	naturally occurring and accelerator-produced materials
NEI	Nuclear Energy Institute
NFS	Nuclear Fuel Services
NIST	National Institute of Standards and Technology
NMSS	Office of Nuclear Material Safety and Safeguards (NRC)
NORM	naturally occurring radioactive material
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OpDCGL	operational DCGL
OK	ordinary kriging
pCi	picocurie
pCi/g	picocurie per gram
pCi/L	picocurie per liter
PNNL	Pacific Northwest National Laboratory
QA	quality assurance
QC	quality control
QAPP	quality assurance project plan
RA	remedial action
RASS	Remedial Action Support Survey
RCRA	Resource Conservation and Recovery Act
REMP	Radiological Environmental Monitoring Program
RESRAD	RESidual RADioactivity software
ROC	radionuclide of concern
RSSI	Radiation Survey and Site Investigation
RTR	research and test reactors
SADA	Spatial Analysis and Decision Assistance
SAFSTOR	long-term storage before decommissioning
SAP	sampling and analysis plan
SER	safety evaluation report
SOF	sum of fractions
SSU	subsurface survey unit
TEDE	total effective dose equivalent
TENORM	technologically enhanced naturally occurring radioactive material

UBGR	upper bound of the gray region
UCL	upper confidence limit
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UXO	unexploded ordnance
VSP	Visual Sample Plan (a software package)
WP3	Work Package 3
WRS	Wilcoxon Rank Sum
+C	plus progeny chain
2D	two dimensional (area)
3D	three dimensional (volume)

1 INTRODUCTION

U.S. Nuclear Regulatory Commission (NRC) guidance for characterization and final status surveys (FSSs) of residual radioactive material at surfaces of soils and structures is found in NUREG-1575, “Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM),” Revision 1 (NRC 2000a), and NUREG-1757, “NMSS Consolidated Decommissioning Guidance.” This guidance is only for contaminants in surficial materials (e.g., the top 15 centimeters (cm) of soils) and is not appropriate for use on subsurface soils (below 15 cm). However, an increasing number of complex decommissioning sites are expected as reactor decommissioning sites multiply. Many of these are reactor sites expected to contain areas of residual radioactivity in subsurface soils. Moreover, instead of entering long-term storage before decommissioning (SAFSTOR), some reactor sites are now being decommissioned soon after shutdown. These facilities will need to be surveyed and the need for subsurface remediation determined. Statistical methods are needed to determine acceptable numbers and distributions of soil samples (or other subsurface media) taken at depth, to maintain appropriate coverage while keeping costs of sampling and analysis reasonable (NRC 2000a and NRC 2006).

KEY POINTS

The following documents are considered essential guidance for subsurface characterization principles:

- International Organization for Standardization (ISO) Standard EN ISO 18557:2020—“Characterization principles for soils, buildings and infrastructures contaminated by radionuclides for remediation purposes”
- American National Standards Institute (ANSI) Standard ANSI/ANS-2.17-2010—“Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Plants”
- NRC-sponsored subsurface software—Spatial Analysis and Decision Assistance (SADA)

Dose modeling is used to determine cleanup levels or derived concentration guideline levels (DCGLs) that meet regulatory criteria for license termination. After remediation has been completed, FSSs need to be conducted to confirm that residual radioactivity remaining at the site meets License Termination Rule (LTR) radiological criteria. While procedures for these surveys and the statistical approaches used for their analysis have been available for surficial contamination in MARSSIM, the NRC is considering developing guidance on these procedures for subsurface contamination.

The objective of this white paper is to assist in developing the technical basis for guidance on conducting and evaluating surveys of residual radioactivity in the subsurface of licensee sites. The technical basis for the guidance includes information on topics such as (1) methods for performing characterization surveys of the subsurface, (2) costs, (3) statistical estimates of optimum numbers and locations of samples, and (4) statistical evaluation of FSSs.

Compliance assessments for surface and subsurface residual radioactivity have similar objectives; both focus on demonstrating that LTR radiological criteria are met. These criteria consider residual radioactivity (1) averaged over the entire site or survey unit and (2) elevated concentrations in smaller areas of the site or survey unit. However, the subsurface presents substantial challenges that add to the complexity of these surveys. First, access to subsurface soils is limited, and surveying subsurface soils is much more expensive than surveying surface soils. Given limited access to subsurface soils, continuous scanning techniques, which are commonly used to provide fast and detailed surveys of the surface, cannot be applied to subsurface soils. Second, subsurface soils can be expected to be heterogeneous in ways that may not be evident. Third, development of DCGLs for subsurface soils is more complex and often involves consideration of various intrusion events that would bring subsurface residual radioactivity to the surface, where a receptor could be exposed. In this regard, ground water exposure pathways also appear to be more important for subsurface contaminants than for contaminants found at the surface. For complex sites that operated over extended times, mobile radionuclides may have been transported deep in the vadose zone and into ground water or fractured rock, further adding to the difficulty in characterizing subsurface residual radioactivity. For these reasons, guidance is needed for the design and implementation of radiological surveys of the subsurface with statistical methods to determine acceptable sample distributions in three dimensions. It is hoped that guidance can be developed to demonstrate the adequacy of site characterization and FSSs by providing reasonable assurance of compliance with radiological criteria while limiting overly conservative approaches.

1.1 CURRENT CRITERIA AND STANDARDS

Guidance from ANSI Standard ANSI/ANS-2.17-2010, "American National Standard—Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Plants" (ANS 2010), is described and implemented with the U.S. Environmental Protection Agency's (EPA's) Triad methodology to allow the extension of MARSSIM to the subsurface using a substantial and continually advancing set of tools including spatial analysis, modeling, and the geographic information system (GIS) community (see Figure 1-1). This standard, developed in 2010 to address subsurface contamination, presents general concepts reinforcing the need for a more tailored approach for NRC licensees that meets regulatory requirements.

In 2020, the ISO published an English version of ISO Standard EN ISO 18557:2020, articulating a set of principles, including geostatistical analysis, for sampling strategy and characterization of soils, buildings, and infrastructure. Annex A to the ISO standard introduces geostatistical data processing and examples of good practices:

> Geostatistics aims to describe structured phenomena in geographic space, possibly in time, and quantify the estimation uncertainties, whether global or local. Estimates are calculated from a partial sampling and result in different representations of the contamination, including interpolation mapping (by a kriging algorithm). But the added value of geostatistics goes beyond this first result, its key feature lies in its ability to quantify estimation uncertainty and provide risk analysis for decision making.

The ISO provides a figure (see Figure 1-2) illustrating the use of geostatistics for characterization of a concrete slab, but the principles can also be applied to subsurface soils (ISO 2020). This white paper explores methodology from the ISO as part of the Triad methodology.

The NRC has sponsored previous work on subsurface modeling and surveys. In point, NUREG/CR-7021, "A Subsurface Decision Model for Supporting Environmental Compliance," issued January 2012 (NRC 2012), outlines an approach to overcoming obstacles to detailed subsurface surveys, but it does not provide details of methods and statistical tests for use in the subsurface. Limitations of access and sampling of the subsurface require an approach that: “maximizes the available information, technologies and expertise; addresses and mitigates sources of uncertainty; and is meaningful within a compliance setting” (NRC 2012). This work will expand on topics in NUREG/CR-7021 addressing decision quality and methods that maximize available information, technologies, and expertise to address and mitigate sources of uncertainty through the EPA’s Triad methodology. Triad allows the extension of MARSSIM to the subsurface using a substantial and advancing set of tools, including spatial analysis, modeling, and the GIS community. Part of the anticipated framework is a particular implementation of the conceptual site model (CSM), called the contamination concern map (CCM). Throughout the Radiation Survey and Site Investigation (RSSI) process, this three-dimensional (3D) model continuously maps and documents knowledge of the extent, location, and severity of contamination relative to the decision criteria.

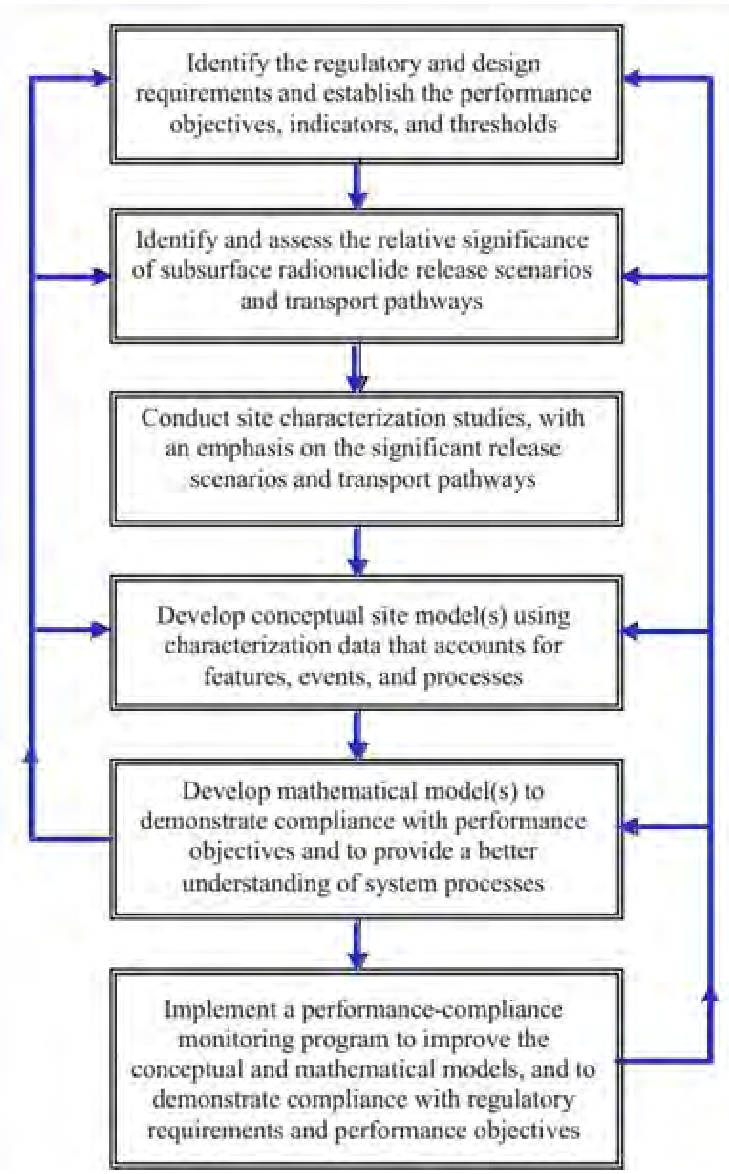

Figure 1-1 Flowchart of Performance Assessment Activities

Source: ANSI 2010

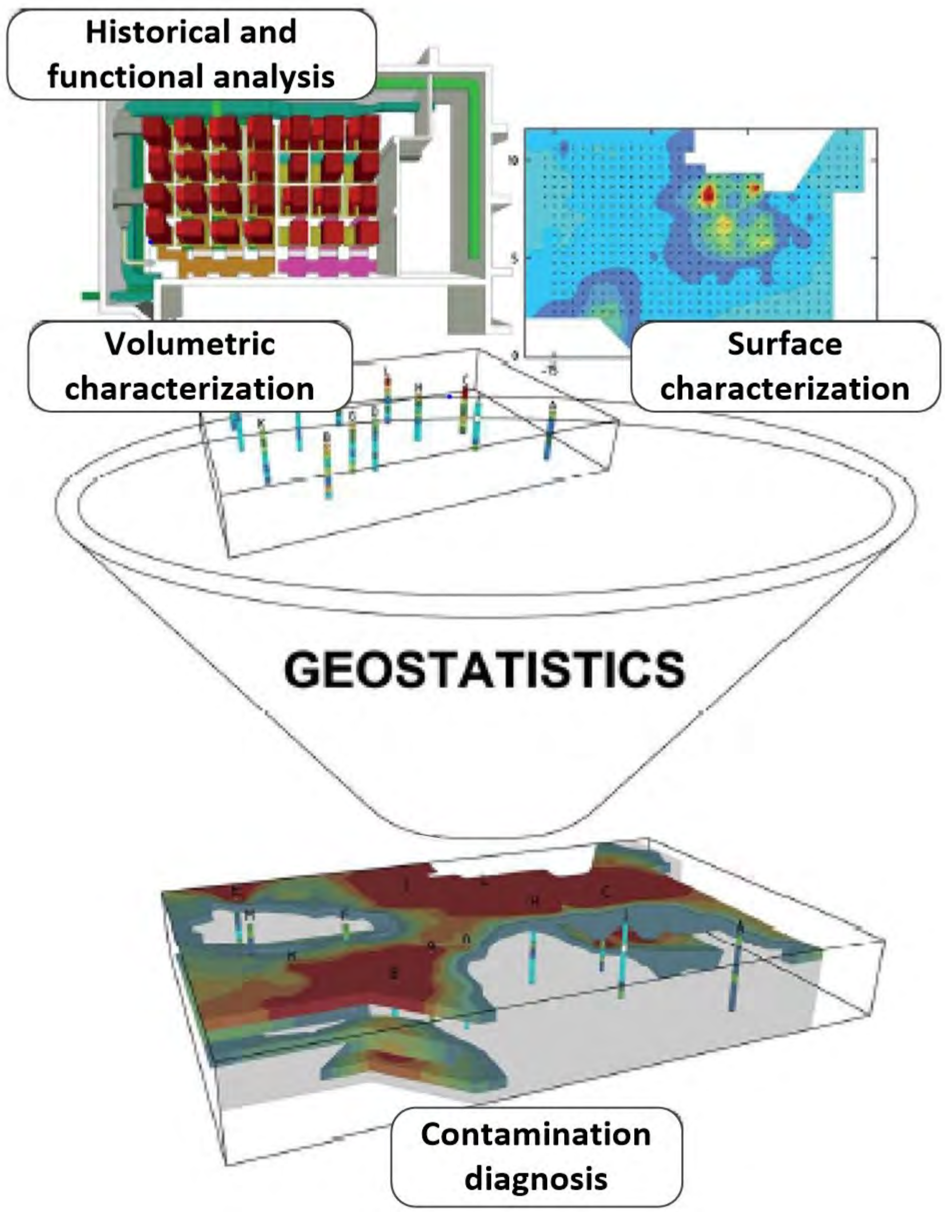

Figure 1-2 Geostatistics Characterization of a Concrete Slab

Source: ISO 2020, Annex A, Figure A.2 (Cited with allowance of Deutsches Institut für Normung eV. The newest version is authoritative for the application of the standard.)

The information presented in this white paper will be the basis for discussions with stakeholders. Their feedback will be considered in the development of recommendations to the NRC on how subsurface contamination can be addressed during decommissioning activities.

1.2 NRC SUBSURFACE SOILS PUBLIC WORKSHOPS

To date, the NRC has held two public workshops, in July 2021 and May 2022, on the technical basis for guidance on conducting and evaluating surveys of residual radioactivity in the subsurface soils of licensee sites. The workshops offered a mix of technical presentations on current considerations and proposed methodologies for the guidance and discussions of stakeholder suggestions and concerns on the topic.

The first workshop took place July 14–15, 2021. Presentations included an overview of the technical letter report prepared by the NRC's contractor, SC&A, Inc., on the technical basis for subsurface guidance and presentations by the industry on the industry's needs with respect to such guidance and current experience with geospatial and statistical-based surveys of subsurface soil. A presenter from Radiation Safety & Control Services in the private sector discussed a graded approach to subsurface characterization and remediation and related tools and methods, building on the conceptual site model approach with geographic information systems, building information models, and a common data environment for a comprehensive picture of the site. Pacific Northwest National Laboratory (PNNL) presented on the Visual Sample Plan (VSP) geospatial statistical methods available to support decommissioning. The workshop also examined the development of subsurface DCGLs, including the effects of thickness, area, and cover, and subsurface hot spots.

The discussion during the first workshop covered the wide range of issues that need to be considered when surveying the subsurface, including the need for a solution that is not overly complex and different approaches based on the amount of site data available. The subsurface also presents different exposure scenarios than the surface, whether through excavation or ground water, and contaminant migration is also a factor. New technologies such as those using artificial intelligence may be useful for identifying subsurface contamination, while those with ground-penetrating capabilities such as lidar would be useful for finding large subsurface structures and boundaries of different types of fill areas. New approaches to sampling the subsurface may also be useful, such as small-scale horizontal borings and cross-hole scans. The presentations for the first annual subsurface workshop can be found at Agencywide Documents Access and Management System (ADAMS) Accession No. ML21208A206, and the associated research information letter is at ADAMS Accession No. ML21300A378.

The second workshop took place on May 11, 2022. It began with NRC presentations on the agency's efforts in this area to date, including on related decommissioning guidance, currently available subsurface guidance, key guidance gaps, and plans for issuance of additional interim guidance. The Nuclear Energy Institute (NEI) discussed its plans to develop NEI 21-01 to standardize the format and content of information to be submitted to the NRC (e.g., final status survey data) to support license termination and shortened decommissioning timelines. More technical presentations included the following:

- SC&A presented on statistical methodologies currently under consideration, specifically describing two features in the Spatial Analysis and Decision Assistance (SADA) code used for survey design: Bayesian Ellipgrid, recommended for initial survey design based on geometrical considerations, and Markov Bayes cokriging, recommended for secondary survey design. Both approaches use prior information from either historical site assessment, expert judgment, or other soft data (such as geophysical data). The presentation also discussed variogram fitting approaches and considerations.

- PNNL presented on data sources and processing, data quality assessment, and analyses to support final compliance/release decision-making. A stratified sampling design was recommended, and layers could be based on either risk or geophysical model output. Geostatistical methods could be used to obtain uncertainty estimates that would inform sample locations. Issues associated with lack of consideration of spatial correlation, even for surface problems, which could lead to higher Type II decision errors (e.g., failure to release clean site in Scenario A), were also discussed.

- Radiation Safety & Control Services presented on the NEI 07-07 ground water protection initiative that begins before decommissioning and provides the support, including hard and soft data, that can be leveraged to support decommissioning. It includes the risk ranking of structures, systems, and components and using trend data from monitoring to identify changes in hydrogeological parameters that may provide important information for dose modeling, contaminant fate and transport, and ground water monitoring. Another presentation provided a historical perspective of survey and dose modeling of reactor basement structures at decommissioned nuclear power plants.

- The U.S. Department of Energy (DOE) discussed DOE Order 458.1 for the release of property and associated dose constraints and a case study that involved the presence of buried radioactive objects at a previously remediated site.

- PNNL discussed geophysical methods in use at DOE and U.S. Department of Defense sites, including technologies, measured properties, and acquisition methods. Methods discussed included electrical resistivity tomography and time-domain electromagnetics.

- Oak Ridge Associated Universities presented on independent verification activities it has performed for the NRC, DOE, and U.S. Army Corps of Engineers and associated lessons learned.

Some workshop participants noted that many decommissioning licensees would not have the resources or need to implement complex methods, and other types of sites are not likely to have significant subsurface contamination. As such, the forthcoming guidance should address the conditions under which it would need to be used. Some participants commented on the need for consensus guidance instead of the case-by-case approach that can lead to less effective decision-making. Recommendations for guidance on surveys of reactor substructures was also discussed. The presentations and meeting summary for the second annual subsurface investigations workshop can be found at ADAMS Accession No. ML22117A070.

2 SURVEY APPROACHES FOR DIFFERENT TYPES OF LICENSEES

This section describes approaches needed for surveys, sampling, and characterization of different types of NRC-licensed sites (e.g., reactors versus materials sites) to show compliance with the License Termination Rule (LTR).

KEY POINTS

- This section describes the LTR and other applicable regulations including EPA's maximum contaminant level (MCL) for drinking water.
- A possible suite of radionuclides is presented with three subsurface soil configurations.
- The RSSI process as it relates to the subsurface is introduced.
- A methodology for scanning surveys with limited physical sampling for validation as an FSS is discussed.

The NRC takes a risk-informed, performance-based approach to the demonstration of compliance (NRC 2006). The survey approaches described in this document will help to identify the information (subject matter and level of detail) needed to terminate a license by considering the specific circumstances of the wide range of NRC licensees beginning with the decommissioning regulations, the anticipated radionuclides, the location of the radionuclides and of course, the unique approach for each licensee. It is anticipated that the NRC will rely on measurable or calculable outcomes (i.e., performance results) to be met, but will allow flexibility in the survey design and implementation technique for subsurface soil issues. The EPA's Triad approach is essential as the techniques involving excavation with surface scanning of thin layers may be cost prohibitive.

2.1 SCOPE OF DECOMMISSIONING REGULATIONS FOR RADIONUCLIDES

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 20, "Standards for Protection against Radiation," states the overarching requirements regulating radiological impacts for facility operations. The framework of regulations may be best understood by first reviewing what the regulations require to restore and release a site at decommissioning. The radiological criteria for license termination are in 10 CFR Part 20, Subpart E, "Radiological Criteria for License Termination." Other applicable requirements of 10 CFR Part 20 are summarized here.

In 10 CFR 20.1003, "Definitions," "residual radioactivity" is defined as follows:

> *Residual radioactivity* means radioactivity in structures, materials, soils, groundwater, and other media at a site resulting from activities under the licensee's control. This includes radioactivity from all licensed and unlicensed sources used by the licensee, but excludes background radiation. 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.

Under 10 CFR 20.1302, "Compliance with dose limits for individual members of the public," a licensee must demonstrate that, during operations and decommissioning, "The annual average concentrations of radioactive material released in liquid effluents at the boundary of the unrestricted area do not exceed the values specified in table 2 of appendix B to part 20." The concentration values are equivalent to the radionuclide concentrations which, if ingested continuously over the course of a year, would produce a total effective dose equivalent (TEDE) of 0.05 rem (50 millirem (mrem) or 0.5 millisieverts (mSv)).

Subpart E of 10 CFR Part 20 includes requirements for unrestricted and restricted use of facilities after license termination (10 CFR 20.1402 and 10 CFR 20.1403, respectively). Subpart E also addresses public participation in the license termination process, the finality of license termination decisions, time periods for dose calculation, alternate dose criteria, and minimization of contamination (NRC 1998a).

The criteria for releasing a site for unrestricted and restricted use are listed here (and summarized in Table 2-1). In NUREG-1575, Supplement 1, "Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME)," issued January 2009 (NRC 2009a), the NRC clarifies that if the compliance scenario is based on the reasonably foreseeable land use, the licensee should provide justification for the scenario, based on discussions with land planners, meetings with local stakeholders, trending analysis of land use for the region, or comparisons with land use in similar alternate locations. The time period of interest for possible land use changes is 100 years, depending on the rate of change in the region and the peak exposure time. Note that the 100-year timeframe described here is only for estimating future land uses; the licensee must evaluate doses that could occur over the 1,000-year time period specified in the LTR. The licensee should identify land uses that are less likely but plausible and evaluate scenarios consistent with these less likely but plausible land uses. In some cases, the determination of reasonably foreseeable land use may require the licensee to evaluate offsite uses of materials containing residual radioactivity as alternate scenarios in defining the compliance scenario (NRC 2009a).

In 10 CFR 20.1402, "Radiological criteria for unrestricted use," the NRC states the following:

> A site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a TEDE to an average member of the critical group that does not exceed 25 mrem (0.25 mSv) per year, including that from groundwater sources of drinking water, and the residual radioactivity has been reduced to levels that are as low as reasonably achievable (ALARA). Determination of the levels which 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 regulation in 10 CFR 20.1403, "Criteria for license termination under restricted conditions," states the following:

> A site will be considered acceptable for license termination under restricted conditions if:
>
> (a) The licensee can demonstrate that further reductions in residual radioactivity necessary to comply with the provisions of § 20.1402 would result in net public or environmental harm or were not being made because the residual levels associated with restricted conditions are ALARA. Determination of the levels

which are ALARA must take into account consideration of any detriments, such as traffic accidents, expected to potentially result from decontamination and waste disposal;

(b) The licensee has made provisions for legally enforceable institutional controls that provide reasonable assurance that the TEDE from residual radioactivity distinguishable from background to the average member of the critical group will not exceed 25 mrem (0.25 mSv) per year;

(c) The licensee has provided sufficient financial assurance to enable an independent third party to assume and carry out responsibilities for any necessary control and maintenance of the site.…

(d) The licensee has submitted a decommissioning plan or License Termination Plan (LTP) to the Commission indicating the licensee's intent to decommission in accordance with §§ 30.36(d), 40.42(d), 50.82 (a) and (b), 70.38(d), or 72.54 of this chapter, and specifying that the licensee intends to decommission by restricting use of the site. The licensee shall document in the LTP or decommissioning plan how the advice of individuals and institutions in the community who may be affected by the decommissioning has been sought and incorporated, as appropriate, following analysis of that advice.

In 10 CFR 20.1401(d), the regulation states, "When calculating TEDE to the average member of the critical group the licensee shall determine the peak annual TEDE dose expected within the first 1000 years after decommissioning."

Table 2-1 Summary of 10 CFR Part 20, Subpart E

	Unrestricted Release	**Restricted Release**	
Dose Criterion	25 mrem TEDE per year peak annual dose to the average member of the critical group	25 mrem TEDE per year peak annual dose to the average member of the critical group while controls are in place	100 mrem or 500 mrem TEDE per year peak annual dose to the average member of the critical group upon failure of controls
Timeframe	1,000 years	1,000 years	1,000 years
Other Requirements	ALARA	ALARA, financial assurance, public participation	ALARA, financial assurance, public participation

Source: NUREG-1549, "Decision Methods for Dose Assessment To Comply with Radiological Criteria for License Termination—Draft Report for Comment," issued July 1998 (NRC 1998b)

Thus, the NRC regulates radioactivity in ground water regardless of whether the material was licensed or unlicensed. Similarly, it does not matter if the release was accidental (e.g., a leak) or intentional (e.g., a planned discharge). It does not matter if the material is in a safety-related pipe or a nonsafety-related pipe. It also makes no difference if the licensee is a complex power plant or a single source material licensee; the same definition of residual radioactivity applies. Surveys of ground water and surface water are required during operations and decommissioning. The level of residual radioactivity is most relevant when a licensee decides to cease operations and must satisfy the NRC's decommissioning requirements (NRC 2010).

Thus, there are two controlling requirements on subsurface radioactivity that determine if a site may be released without restrictions: (1) a 25-mrem per year limit for all exposure pathways, including from drinking water, ground water, or both and (2) reducing the residual radioactivity, which includes activity in ground water, to ALARA. ALARA means making every reasonable effort to keep exposures to radiation as far below the dose limits as is practical consistent with the purpose for which the licensed activity is undertaken, while considering the state of technology, the economics of improvements in relation to the state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest (NRC 2010).

Under 10 CFR 20.1501, "General," licensees are required at all times, including operations and decommissioning, to conduct surveys to determine, among other things, concentrations or quantities of radioactive material and potential radiological hazards. These surveys must be reasonable under the circumstances to evaluate ground water radioactivity to the extent that it may be necessary for the licensee to comply with the regulations in 10 CFR Part 20. Additionally, licensees are required to maintain records for purposes of tracking spills and leaks (NRC 2010).

As discussed, ALARA principles apply to doses associated with ground water contamination (see 10 CFR 20.1402).

The NRC formed a Groundwater Contamination Task Force (GTF)[1] due to incidents[2] at Oyster Creek, Oconee, and Vermont Yankee nuclear power plants (NPPs) resulting in the detection of tritium in ground water monitoring wells. These incidents have caused NRC licensees and the NRC to take actions to address the source of the tritium (e.g., buried piping leaks) and to communicate the impact to the public and other external stakeholders. The following subsections (2.1.1–2.1.4) are based on the GTF report and provide an overview of facility operations related to ground water contamination and the governing regulations for each type of licensee (NRC 2010). The different kinds and types of operations will influence the approach and techniques in the FSS.

2.1.1 Decommissioning Reactors

Release of all or part of a site after decommissioning makes it available to members of the public for use with or without restrictions. The NRC has requirements for areas to be released from the license in 10 CFR 50.82, "Termination of license," and 10 CFR 50.83, "Release of part of a power reactor facility or site for unrestricted use" (these sections incorporate 10 CFR 20.1402 and 10 CFR 20.1403). To comply with these regulations, the licensee conducts sampling and monitoring to accurately define all radioactivity remaining on the site. Following remediation, as defined in the license termination plan (LTP) or request for partial site

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1 The NRC's Executive Director for Operations established the GTF in a memorandum to Bruce Mallett and Charles Casto, dated March 5, 2010 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML100640188) (NRC 2010b). The memorandum includes the GTF charter.

2 "List of Historical Leaks and Spills at U.S. Commercial Nuclear Power Plants," Revision 12, December 4, 2013 (ADAMS Accession No. ML101270439) (NRC 2013b). Note: The GTF reviewed selected events since 2006.

release, ground water must be sampled for residual radioactivity, according to an approved scheme, to demonstrate compliance with release criteria (NRC 2010b). In addition to NRC requirements, as mentioned earlier, the NRC has entered into a memorandum of understanding (MOU) with the EPA on cleanup of radioactively contaminated sites. This MOU includes provisions for NRC and EPA consultation for certain sites, including when contamination exceeds EPA-permitted levels at the time of license termination (NRC 2010).

2.1.2 Research and Test Reactors

Research and test reactors (RTRs) share the same regulatory framework discussed in Section 2.1.1, with the exception of requirements outlined in 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," and Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants." General design criteria requirements to control and monitor liquid releases to the environment and quality assurance (QA) program requirements do not apply to RTRs. Historically, RTRs have promptly informed the NRC whenever a leak has been detected. RTRs are also required to provide annual reports to the NRC that summarize the nature and amount of radioactive effluents released to the environment, including primary coolant leakage. RTR pool leaks are identified primarily through pool water inventory balance calculations with the radionuclides being released (primarily tritium and sodium-24) identified by means of periodic pool water sample analysis. During normal operation, maximum concentrations of radionuclides in the primary coolant remain relatively constant, and in some cases, these facilities use primary coolant radiation monitors to detect any sudden increase in radionuclide concentration of the reactor pool water. There are no requirements for ground water samples of the environment surrounding RTR facilities. As part of the RTR license renewal process, the NRC staff does request that these facilities analyze the radiological impact of any primary coolant leakage to the environment, if applicable (NRC 2010).

2.1.3 Fuel Cycle Facilities

Similar to reactor facilities, operating fuel cycle facilities are regulated under 10 CFR Part 70, "Domestic Licensing of Special Nuclear Material," and 10 CFR Part 20. Within 60 days after January 1 and July 1 of each year, 10 CFR Part 70 licensees are required to submit a report to the NRC specifying the quantity of each of the principal radionuclides released to unrestricted areas in liquid and gaseous effluents during the previous 6 months of operation (as required by 10 CFR 70.59, "Effluent monitoring reporting requirements"). Licensees under 10 CFR Part 70 are subject to various reporting and notification requirements including 10 CFR 70.50, "Reporting requirements," and 10 CFR 70.52, "Reports of accidental criticality." For monitoring onsite contamination, a preoperational program that documents background levels of radioactivity may not be required. Additionally, specific offsite environmental pathways may not be routinely sampled at the site boundary.

- For spills, 10 CFR 20.1406, "Minimization of contamination," requires licensees to keep records of information important to the safe and effective decommissioning of the facility.

- The performance requirements for facilities to which Subpart H, "Additional Requirements for Certain Licensees Authorized To Possess a Critical Mass of Special Nuclear Material," of 10 CFR Part 70 (10 CFR 70.61, "Performance requirements") applies call for certain monitoring and notifications:

  - Protection of the environment only involving human interaction is considered.

– A dose assessment will be conducted, should a spill occur and if a viable pathway to members of public is identified, in order to—

  - Provide data on quantities of radioactive material released in liquid and gaseous effluents.

  - Provide data on measurable levels of radiation and radioactive materials in the environment.

  - Identify needed changes in the use of unrestricted areas (e.g., for agricultural purposes) to permit modifications in monitoring programs for evaluating doses to individuals from the principal pathways of exposure.

Also, just as with reactors and other operations that are a part of the nuclear fuel cycle, pursuant to 10 CFR 20.2203(a)(4), fuel cycle licensees are subject to the provisions of the EPA's generally applicable standards in 40 CFR Part 190, "Environmental Radiation Protection Standards for Nuclear Power Operations." These licensees are required to submit a report for levels of radiation or releases of radioactive material in excess of those standards or of license conditions related to those standards (NRC 2010).

2.2 U.S. EPA INVOLVEMENT

The NRC has entered into an MOU[3] with the EPA on cleanup of radioactively contaminated sites. This MOU includes provisions for NRC and EPA consultation[4] for certain sites including cases in which, at the time of license termination, contamination exceeds EPA-permitted levels (NRC 2006). A letter from the NRC to the EPA, dated June 3, 2020 (ADAMS Accession No. ML20107H268), and the EPA's response, dated August 11, 2020 (ADAMS Accession No. ML20226A048), clarified the scope of the EPA MOU. Specifically, the letters clarified that uranium recovery and mill tailings disposal sites decommissioned pursuant to the criteria in 10 CFR Part 40, "Domestic Licensing of Source Material," Appendix A, "Criteria Relating to the Operation of Uranium Mills and the Disposition of Tailings or Wastes Produced by the Extraction or Concentration of Source Material from Ores Processed Primarily for Their Source Material Content," are outside the MOU's scope. The EPA confirmed this interpretation to be consistent with the MOU's development and implementation.

If the water releases from a facility could impact a community water service, the releases may be regulated by the Safe Drinking Water Act (SDWA 2019). A community water service includes any drinking water system, regardless of ownership, that has at least 15 service connections or regularly serves at least 25 of the same people year round. Other regulatory stakeholders may have authority over water issues as site-specific agreements and decisions may have been made with States, Tribes, and the EPA. The impact of water on DCGLs and FSSs has a history at several large sites and is discussed in Section 10 of this white paper.

The EPA limits on drinking water are called maximum contaminant levels (MCLs) for four groupings of radionuclides, as shown in Table 2-2.

3 http://www.nrc.gov/reading-rm/doc-collections/news/2002/mou2fin.pdf

4 https://www.nrc.gov/waste/decommissioning/reg-guides-comm/comm/letters.html

Table 2-2 EPA Radionuclide MCLs in Drinking Water

Radionuclide Maximum Contaminant Levels	
Beta/photon-emitters[a]	4 mrem/year
Gross alpha	15 picocuries per liter (pCi/L)
Radium-226 and radium-228	5 pCi/L
Uranium	30 micrograms per liter (µg/L)

[a] A total of 179 individual beta particle and photon emitters may be used to calculate compliance with the MCL.

Source: EPA 2002a, EPA 2020

Table 2-3 presents the derived MCLs in pCi/L of beta- and photon-emitters in drinking water according to the methodology in the National Bureau of Standards (NBS) Handbook 69, “Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure,” issued August 1959 (NBS 1959), yielding a dose of 4 mrem/year to the total body or to any critical organ. If multiple radionuclides are present, a sum of fractions (SOF) rule is applied (EPA 2002a). However, MCLs do not have an impact on the FSS’s ability to meet the LTR.

Table 2-3 MCLs of Beta- and Photon-Emitters in Drinking Water

Nuclide	pCi/l	Nuclide	pCi/l	Nuclide	pCi/l	Nuclide	pCi/l	Nuclide	pCi/l	Nuclide	pCi/l
H-3	20,000	Ni-65	300	Nb-95	300	Sb-124	60	Nd-147	200	Os-191	600
Be-7	6,000	Cu-64	900	Nb-97	3,000	Sb-125	300	Nd-149	900	Os-191m	9,000
C-14	2,000	Zn-65	300	Mo-99	600	Te-125m	600	Pm-147	600	Os-193	200
F-18	2,000	Zn-69	6,000	Tc-96	300	Te-127	900	Pm-149	100	Ir-190	600
Na-22	400	Zn-69m	200	Tc-96m	30,000	Te-127m	200	Sm-151	1,000	Ir-192	100
Na-24	600	Ga-72	100	Tc-97	6,000	Te-129	2,000	Sm-153	200	Ir-194	90
Si-31	3,000	Ge-71	6,000	Tc-97m	1,000	Te-129m	90	Eu-152	200	Pt-191	300
P-32	30	As-73	1,000	Tc-99	900	Te-131m	200	Eu-154	60	Pt-193	3,000
S-35 inorg	500	As-74	100	Tc-99m	20,000	Te-132	90	Eu-155	600	Pt-193m	3,000
Cl-36	700	As-76	60	Ru-97	1,000	I-126	3	Gd-153	600	Pt-197	300
Cl-38	1,000	As-77	200	Ru-103	200	I-129	1	Gd-159	200	Pt-197m	3,000
K-42	900	Se-75	900	Ru-105	200	I-131	3	Tb-160	100	Au-196	600
Ca-45	10	Br-82	100	Ru-106	30	I-132	90	Dy-165	1,000	Au-198	100
Ca-47	80	Rb-86	600	Rh-103m	30,000	I-133	10	Dy-166	100	Au-199	600
Sc-46	100	Rb-87	300	Rh-105	300	I-134	100	Ho-166	90	Hg-197	900
Sc-47	300	Sr-85 m	20,000	Pd-103	900	I-135	30	Er-169	300	Hg-197m	600
Sc-48	80	Sr-85	900	Pd-109	300	Cs-131	20,000	Er-171	300	Hg-203	60
V-48	90	Sr-89	20	Ag-105	300	Cs-134	80	Tm-170	100	Tl-200	1,000
Cr-51	6,000	Sr-90	8	Ag-110m	90	Cs-134m	20,000	Tm-171	1,000	Tl-201	900
Mn-52	90	Sr-91	200	Ag-111	100	Cs-135	900	Yb-175	300	Tl-202	300
Mn-54	300	Sr-92	200	Cd-109	600	Cs-136	800	Lu-177	300	Tl-204	300
Mn-56	300	Y-90	60	Cd-115	90	Cs-137	200	Hf-181	200	Pb-203	1,000
Fe-55	2,000	Y-91	90	Cd-115m	90	Ba-131	600	Ta-182	100	Bi-206	100
Fe-59	200	Y-91m	9,000	In-113m	3,000	Ba-140	90	W-181	1,000	Bi-207	200
Co-57	1,000	Y-92	200	In-114m	60	La-140	60	W-185	300	Pa-230	600
Co-58	300	Y-93	90	In-115	300	Ce-141	300	W-187	200	Pa-233	300
Co-58m	9000	Zr-93	2,000	In-115m	1,000	Ce-143	100	Re-186	300	Np-239	300
Co-60	100	Zr-95	200	Sn-113	300	Ce-144	30	Re-187	9,000	Pu-241	300
Ni-59	300	Zr-97	60	Sn-125	60	Pr-142	90	Re-188	200	Bk-249	2,000
Ni-63	50	Nb-93m	1,000	Sb-122	90	Pr-143	100	Os-185	200		

Source: EPA 2002a

2.3 ANTICIPATED RADIONUCLIDES

A unique radionuclide profile must be developed for each of the major types of materials expected to remain on site after remediation. A commercial light-water power reactor facility will likely require profiles for contaminated soil or sediments, surface contaminated materials, and activated materials. The licensee must consider that activation products in steels and concretes vary with the constituents and operational history. Concrete will also differ between facilities because of different trace elements. While one generic list cannot be developed that would apply to all licensees and types of contaminated materials, once radioactive decay has been considered to the time when FSSs will be conducted, a set of radionuclides may be developed for surface contamination and for activated materials. The profiles listed for commercial NPPs in Table 2-4 are not meant to be all-inclusive, and other radionuclides should be added, as necessary, based on site-specific considerations (NRC 2006).

A series of uncontrolled releases of radionuclides (principally tritium) to the subsurface at NPPs has occurred over the past decade. These releases originated from nuclear plant structures, systems, and components that store or convey liquids and gases containing radionuclides; and leaks from spent fuel pools, vacuum breakers, pipes within concrete pipe vaults, buried pipes, and condensate storage tanks. Although the radionuclides released from these underground leaks primarily consisted of tritium, the contamination often included a variety of radionuclides unique to each plant (in one case, strontium-90, nickel-63, and cesium-137) (see Table 2-5 for a ranked list of radionuclides (Nicholson et al. 2011).

Non-NPP licensees will each have a unique suite of radionuclides.

Table 2-4 Example NPP Radionuclide Profile

Combination Suite		Activation Suite
H-3	Sb-125	H-3
C-14	Cs-134	C-14
Mn-54	Cs-137	Fe-55
Fe-55	Eu-152	Ni-63
Co-57	Eu-154	Co-60
Co-60	Ce-144	Cs-134
Ni-59	Pu-238	Eu-152
Ni-63	Pu-239/240	Eu-154
Sr-90	Pu-241	Eu-155
Nb-94	Am-241	Mn-54,
Tc-99	Cm-243/244	Ni-59, Zn-65

Source: Appendix O[9] to NUREG-1757, "Consolidated Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Criteria," Volume 2, Revision 1, issued September 2006 (NRC 2006)

Table 2-5 Ranked List of Radionuclides at Commercial Nuclear Pressurized-Water Reactor Power Plants Based on Their Relative Abundance, Activity, and Transport Characteristics

Relative Rank	Radionuclide	Half-Life[a] (days)
1	Sr-90	1.06×10^{4}
2	Cs-137	1.10×10^{4}
3	Co-60	1.93×10^{3}
4	H-3	4.51×10^{3}
5	Cs-134	7.33×10^{2}
6	I-129	5.73×10^{9}
7	Ni-63	3.51×10^{4}
8	C-14	2.09×10^{6}
9	Pu-238	3.20×10^{4}
10	Am-241	1.58×10^{5}

[a] NUREG/CR-5512, "Residual Radioactive Contamination from Decommissioning," Volume 1, "Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent" (Kennedy and Strenge 1992)
Source: Nicholson et al. 2011 (from Scott 2008)

9 Page iv of NUREG-1757, Volume 2, Revision 2, indicates that the NRC removed the discussion of lessons learned from Appendix O in Revision 1 of that report. The NRC's decommissioning Web site should be consulted for issuance of technical reports providing guidance and a listing of any lessons learned between guidance revisions (https://www.nrc.gov/waste/decommissioning/lessons-learned.html).

2.4 INITIAL LOCATION OF RADIONUCLIDES

2.4.1 Initial Location of Primary Contamination for RESRAD Inputs

To facilitate survey design for surface soils and ensure that the survey data points for a specific site are relatively uniformly distributed among areas of similar contamination potential, the site is divided into survey units that share a common history or other characteristics or that are naturally distinguishable from other portions of the site (NRC 2000a). This does not necessarily work for subsurface soils as underground portions may not be distinguishable from each other. However, modeling must begin with certain assumptions, and the primary computer code in use, RESRAD-ONSITE, has established many input parameters. RESRAD-OFFSITE places the primary contamination (the initial location of radionuclides) as a layer of soil that is either directly contaminated or contains radionuclide-bearing material distributed within it. This is relevant for all types of licensees. RESRAD-OFFSITE assumes that the primary contamination is uniformly distributed and is of a constant thickness. There can be a layer of clean cover on top of the primary contamination. RESRAD-ONSITE assumes that radionuclides are uniformly distributed within the contaminated zone, and for modeling, the average thickness of a layer is used (Yu et al. 2001). The primary contamination can be above the water table, it can straddle the water table, or it can be submerged with its top at the water table, as shown in Figure 2-1 (NRC 2020d). Although the RESRAD-OFFSITE user manual identifies certain verification, benchmarking, and validation, it should be used with caution as it was recently published in 2020, and its capability and efficacy have not been tested in establishing DCGLs below the water table.

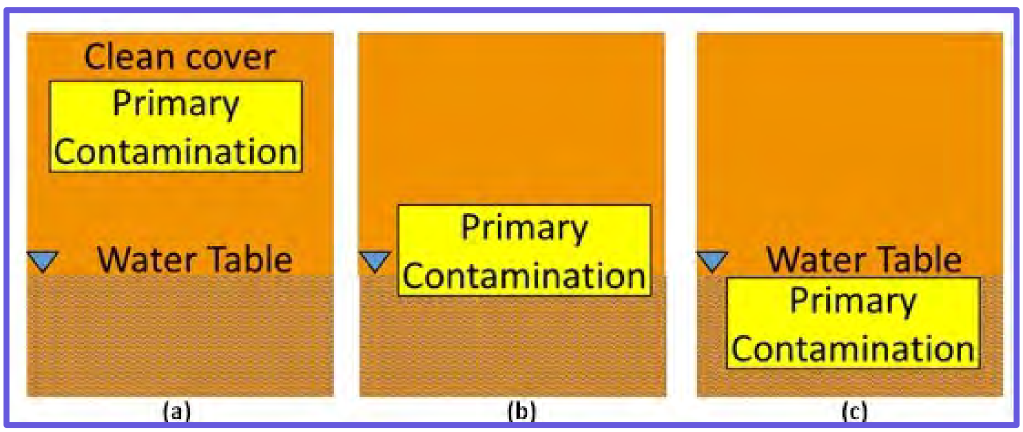

Figure 2-1 Locations of Primary Contamination

Source: NRC 2020d

2.4.2 Other Contaminated Locations on Remaining Structure

In some cases, the site may have below-grade basements (perhaps deeper than 3 meters (m)) that will be backfilled and remain after decommissioning. For these sites, some residual radioactivity may be left on the concrete surfaces before backfill, and a different conceptual model is warranted to derive site-specific DCGLs for those concrete surfaces. Standard scenarios could be developed for large basement substructures as discussed in Appendix J to NUREG-1757, Volume 2, Revision 2 (NRC 2020c), although there might be some site-specific considerations particularly for structures located below the water table. RESRAD can still be used, but other calculations and codes may help supplement the effort. NUREG-1757, Volume 2, Revision 2, Appendix J, provides guidance on the development of exposure scenarios for buried radioactivity, including exposure scenarios that may need to be considered for large reactor basements, although site-specific considerations may also require consideration (e.g., for structures located below the water table). While in certain cases, simplifying assumptions may be made in RESRAD, supplemental calculations and codes may be needed to demonstrate compliance with release criteria described in Sections 6 and 10. Figure 2-2 illustrates an example of a contaminated basement floor and walls that are not to be demolished.

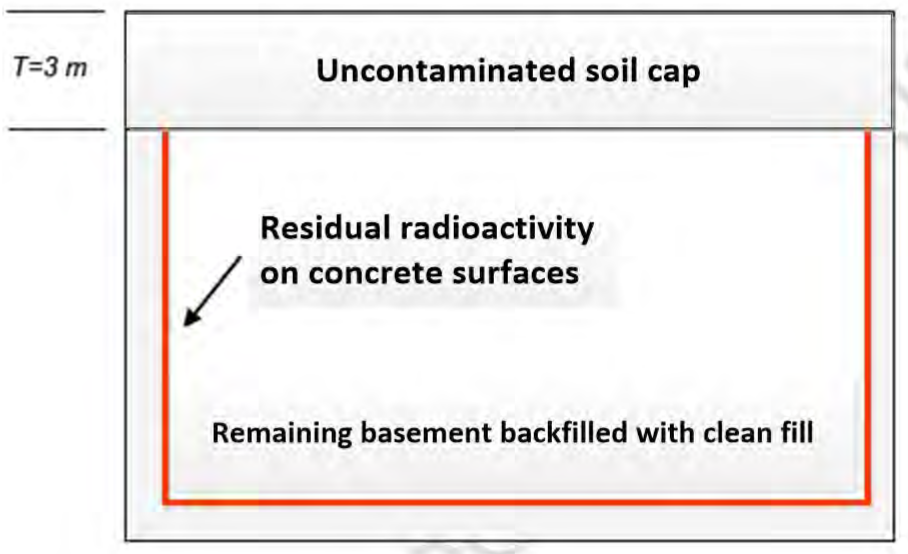

Figure 2-2 Example of Contaminated Basement Backfilled with Clean Fill

Source: NRC 2020c

2.5 SURVEY APPROACHES

This document discusses a MARSSIM-like survey approach to the three configurations of primary contamination and other intrusion scenarios for residual radioactivity left behind in decommissioning. The approach includes scoping, characterization, remedial, and compliance surveys. Techniques are presented to calculate the total volume required, if any, for removal (remediation).

The licensee should first determine whether it needs surveys of subsurface residual radioactivity. The historical site assessment (HSA) (see Section 5.2) and other surveys will play an important role in determining whether there is likely to be residual radioactivity in the subsurface. Modeling can also be used to supplement survey data to determine the potential for residual radioactivity to be present in significant quantities in subsurface soils or ground water due to environmental transport. If the survey data and supplemental modeling indicate that there is little likelihood of significant subsurface residual radioactivity, then subsurface surveys are likely unnecessary (NRC 2020b).

If the survey data indicate that there is substantial subsurface residual radioactivity, and the licensee plans to terminate the license with some subsurface residual radioactivity in place, the FSS should consider the subsurface residual radioactivity to demonstrate compliance with the radiological criteria for license termination. To prepare for the FSS, the characterization survey determines the depth of the residual radioactivity. In addition to conventional drilling, the licensee may consider the use of geoprobe, or exploratory trenches and pits, where the patterns, locations, and depths are determined using prior survey results or HSA data (NRC 2020b). Section 5 presents detailed discussions of these topics (HSA, scoping, characterization surveys, remedial surveys, and FSS) and how they may intersect or overlap.

Performing radiological surveys at sites with significant quantities of subsurface residual radioactivity is more complex than surveying surface soils given the relative inaccessibility of the subsurface regions (e.g., subsurface soils cannot be scanned for elevated areas without the extraction of subsurface materials). Additionally, heterogeneous materials are often encountered in the subsurface, and the presence of contaminated ground water also presents challenges to subsurface radiological surveys (see NUREG-1757, Volume 2, Revision 2, Appendix F). Because the MARSSIM methodology relies heavily on scanning to identify elevated areas of concern (AOCs), alternative or supplemental methods are needed when residual radioactivity is present in the subsurface. Modeling may help inform and supplement collection of radiological survey data and help alleviate the challenge of adequately characterizing the subsurface when scanning is not a viable option. NUREG/CR-7021 (NRC 2012) presents a framework focused on development of a CSM referred to as a “contamination concern map” (CCM). The CCM describes the extent, location, and significance of residual radioactivity relevant to the decision criteria. The CCM can be developed with the aid of visualization, a geographic information system (GIS), and geostatistical software. As additional data are collected, the CCM transitions from a mostly qualitative description to a more quantitative and detailed map. Subsurface concentration estimates and uncertainty measures are surrogates to scanning to facilitate better sampling designs and decision-making. The approach laid out in NUREG/CR-7026, “Application of Model Abstraction Techniques To Simulate Transport in Soils,” issued March 2011 (NRC. 2011), presents one potentially acceptable method that may be used in conjunction with radiological survey data to demonstrate compliance. For complex decommissioning cases with subsurface residual radioactivity and ground water contamination, it is important to work with the NRC early in the process to discuss acceptable approaches for demonstrating compliance with radiological criteria for license termination (NRC 2020b).

GIS and geostatistical software are available to assist with designing, performing, and evaluating the results of radiological investigations. GIS tools can be used to help with creation of conceptual models (e.g., by providing spatial context and a better understanding of site features that may control or enhance radionuclide transport in the environment). Figures created with GIS software can also assist with identifying relatively homogeneous areas of residual radioactivity for delineation of survey units. Geostatistical tools can be used to create figures showing contaminant distributions, predict radionuclide concentrations in areas where no data exist, and identify areas with a higher probability of residual radioactivity above levels of concern. This information can be beneficial in designing the scoping, characterization, and remediation surveys (see Section 5) to define the nature and extent of residual radioactivity (e.g., by optimizing the number and locations of samples) (NRC 2020b).

The MARSSIM RSSI process includes survey approaches for scoping, characterization, remediation, and final status. Beginning with the HSA, both DCGLs and the CCM should be updated and verified as appropriate before moving to the next phase (see Figure 2-3). The NRC approves the final DCGLs usually through approval of the LTP and the LTP application, and license conditions are usually written to allow some flexibility in the DCGLs under certain specified conditions. Otherwise, the NRC would need to approve any changes to the DCGLs. For example, a final DCGL, especially when DCGLs are established for surrogates, would be appropriate at the FSS if the ratios remain valid. New data collected during the RSSI process may not invalidate the DCGLs. The licensee may choose to use the DCGLs that it established with the approval of the LTP. The licensee may make the DCGLs more conservative, and it is up to the licensee to decide whether to use them. Before use of the DCGLs at the FSS, licensees should review the CCM and associated site physical data to assess whether the DCGLs remain appropriate so as not to underestimate potential dose. When the NRC staff reviews the FSS strategy and final status survey report (FSSR), it evaluates the summary of the site physical data collected during each phase, as well as the CCM, to determine if the DCGLs applied remain realistically conservative.

Compounding the issues is that multiple DCGLs may be required. In many cases, licensees have used a layered approach in which multiple subsurface layers or strata are considered individually, and then the cumulative risk from the multiple layers or strata is assessed. After the remedial work, multiple sets of DCGLs may have been approved for different strata or layers below final grade based on dose modeling. For example, surface soil is important to the external dose and inhalation pathways, intermediate depth soil corresponding to the till depth is potentially important to the plant ingestion pathway, and subsurface soil may be important to the ground water pathway. Intrusion scenarios are considered to develop subsurface DCGLs for otherwise inaccessible subsurface soils at depth. In cases where different sets of DCGLs are developed for different strata, it is important to ensure that the average contaminant concentration in each designated stratum is lower than the applicable DCGL and that any elevated areas are appropriately investigated and addressed. An SOF approach can be used to assess the cumulative risk associated with multiple strata (NRC 2020b). Section 3 and Section 5.5 discuss development of DCGLs and remedial surveys, respectively.

In 2012, NRC published NUREG/CR-7021, which describes Spatial Analysis and Decision Assistance (SADA) software. SADA incorporates use of an evolving CCM and introduces the concept “Check and Cover.” The SADA software provides a number of *informed* initial design strategies, in which the CCM is used to assist in survey design along with the Check and Cover strategy (Stewart et al. 2009). As described in NUREG/CR-7021, this sample design seeks to check those locations where contamination is more likely to exist while at the same time providing some coverage to low-probability areas. Unfortunately, the module to perform the function of Check and Cover is not available in the free downloadable Version 5.0.78; Section 6 discusses Check and Cover in more detail.

Figure 2-3 illustrates the relationships of the RSSI process and the required DCGL potential updates and the CCM as narrated in NUREG/CR-7021. The licensee may update DCGLs at any stage, but the levels should be reviewed after approval by the NRC throughout the RSSI process to ensure they remain valid.

The CCM should be updated throughout each phase of the RSSI process. Keeping records during each phase will show how the contamination levels change from phase to phase to inform cleanup and license termination decision-making. Using CCMs and SADA is meant to help provide a scientific evaluation of what cannot be seen or scanned underground. The RSSI process can become somewhat complicated, as shown in Figure 2-3.

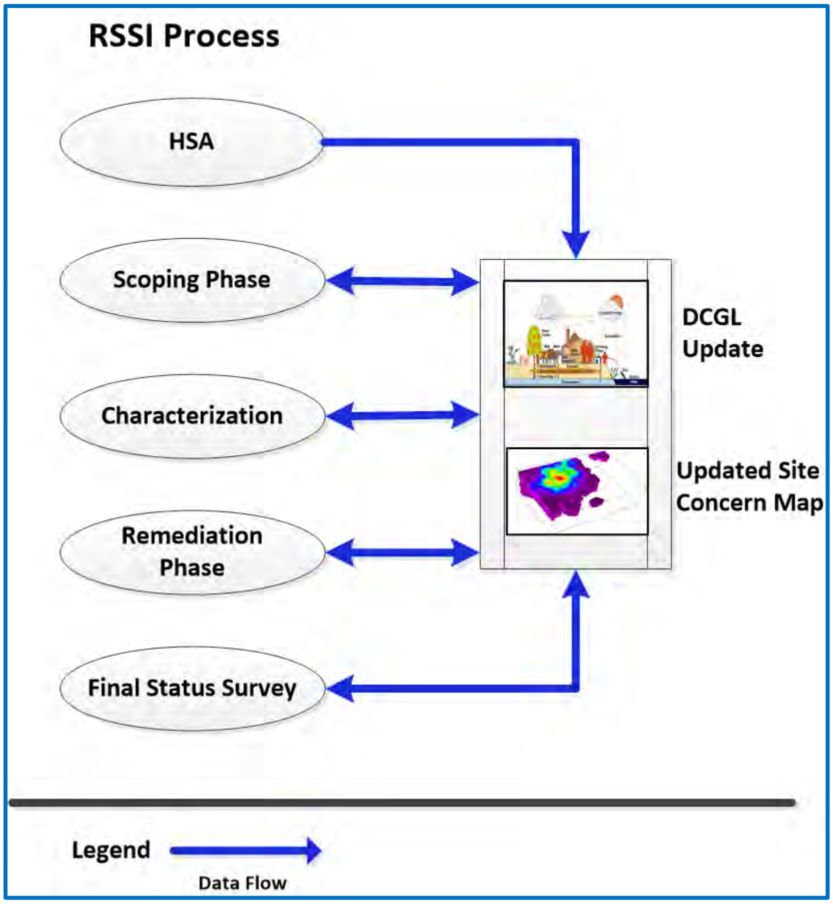

Figure 2-3 DCGL and CCM Updates in the RSSI Process

Much of this document will assist in the development of inputs required for the RESRAD-ONSITE code.

***Approaches to Subsurface Assessments*—**In a surface assessment, exposure scenarios are well defined, measurements are easily accessible, and comprehensive scans provide a safety net to ensure that a survey unit is safe. MARSSIM takes advantage of these factors through a well-defined set of hypothesis tests and scanning technologies to determine the number and placement of samples. In the subsurface, exposure scenarios are less clear, measurements are highly inaccessible, and no comprehensive scans exist. In lieu of some technological breakthrough in subsurface measurements, only two approaches exist (Stewart 2012):

(1) Continue to approach the problem in a rigid and classic manner despite the lack of comprehensive scanning data and the cost of sample collection. Accept quality measurements, and use only simple, formal hypothesis tests. The samples are likely to be few in number, highly correlated, and poorly representative of the total volume of the study area. While a MARSSIM-style hypothesis test, such as Sign Test or Wilcoxon Rank Sum (WRS) test, can certainly be applied, its practical worth may be highly questionable without a clear exposure outcome that depends on the site average.

(2) Dig up the entire site and sample or scan as you go. For example, scrape off a few inches to a foot or so at a time, and repeat MARSSIM on each revealed surface until a level is reached that passes.

Issues with Applying MARSSIM to the Subsurface—In the MARSSIM framework, a site is divided into homogeneous geographic areas called *survey units.* A survey unit is a geographic area with a specific size and shape that will serve as the basis of the investigation and the decision as to compliance with release criteria. The source of the contaminant usually defines the survey unit volume and is informed by the HSA. Buried waste takes one approach, a leak from a pipe takes another, and a spill at the surface requires a third. The issue has less to do with the characteristics of the subsurface itself than the means of emplacing the contaminant and its subsequent behavior specific to transport. Thus, a leak from a subsurface pipe is a different kind of survey unit than a spill at the surface or buried waste.

Subsurface contamination also presents circumstances that do not warrant a direct application of MARSSIM.

- First, the calculation of a DCGL designed for wide-area surface soil ($DCGL_W$) is problematic. One would need to formulate an exposure scenario that would occur in the subsurface. Examples include ground water contamination scenarios and future scenarios in which the subsurface is disturbed by bringing it to the surface (e.g., excavation). As described earlier, NUREG-1757 provides a model example for buried radioactive material, which is illustrated in Section 4.3 and is the basis for the modeling described in Section 2. The derived concentration guideline level for elevated measurement comparison ($DCGL_{EMC}$) may also be problematic. Both assume that some reasonable future scenario is available and both DCGLs can be computed (Stewart 2012) even though the excavation may result in the mixing of the uncontaminated cover material with the contaminated material underneath and the redistribution of the mixed material on the surface. However, no credit for concentration reduction as the result of mixing should be taken if the undisturbed contaminated layer is exposed at the surface (Yu et al. 2001).[10] Both the intrusion and the "as is" scenarios should be evaluated. Alternatively, an analysis could be performed that considers the surface soil above the top of the buried residual radioactivity removed (see Figure J.1 in NUREG-1757, Volume 2, Appendix J). In this case, the vadose zone thickness should be based on the actual depth to ground water from the bottom of the buried residual radioactivity. In many cases, the dose from the intrusion scenario will be higher, particularly if direct exposure pathways dominate the dose. However, for radionuclides whose dose is dominated by the ground water pathway, the dose from the "as is" configuration would likely be most limiting.

- The second problem arises in the definition of the statistical population and the $DCGL_W$. Statistical hypothesis testing assumes that the samples come from the same population. That is, nothing fundamentally different is occurring to imply that sampling has occurred over two populations. In the subsurface, this may not be the case. Different depth layers may be characterized by changes in soil type and density. Water content, soil chemistry, and the like may cause changes in the underlying support. In other words, it is inconceivable that if N samples are required for the presumably homogeneous surface, N samples would suffice for the subsurface under an assumption of complete

[10] Erosion leading to uncovering of the contamination at depth might happen over time, with uncertainty in the timing.

homogeneity. The naïve grouping of all samples into a classic hypothesis test will likely fall short of any decisional merit. Therefore, from a cost perspective, the number of samples would need to increase, potentially straining budgetary resources. This problem is precisely the challenge addressed by Triad (Stewart 2012).

The greatest difficulty stems from the inability of investigators to completely scan the subsurface. The lack of comprehensive coverage so easily gained at the surface now presents a real obstacle in determining activity levels at depth. For gamma-emitters, such as cesium-137 and cobalt-60, scanning boreholes is possible; however, it is difficult to specify a geometry for the source term, thereby limiting the interpretation of count data in terms of activity levels and location (Stewart 2012).

Historically, the focus on “data quality” has been on analytic quality, which in practice emphasizes the highest possible accuracy for each measurement. Unfortunately, higher analytic accuracy comes with a higher cost. As a result, project managers may necessarily limit the number of samples collected (Crumbling 2004). Triad approaches this problem by expanding the concept of data quality from an analytic viewpoint to a decision support viewpoint. Furthermore, emphasis is placed on the use of alternative and real-time measurements, along with alternative lines of evidence to inform understanding and clarify uncertainty (Stewart 2012). Use of innovative techniques and real-time measurements with state-of-the-art instrumentation trumps overly accurate sampling results which wastes valuable time and dollars.

Approaches to the Assessment of Excavated Subsurface Soils—MARSSIM, draft Revision 2 (NRC 2020b), permits the use of scanning techniques for gamma emitters without comprehensive physical samples for demonstrating that concentrations of radioactive material do not exceed release criteria. Such surveys can be used for the subsurface when applied to bottoms and side slopes of trenches and spread-out layers from stockpiles for segregation or backfill. Chapter 11 discusses robotic survey platforms related to scanning techniques.

A scanning methodology might be considered a paradigm shift from the requirements in MARSSIM, Revision 1. The scan minimum detectable concentration (MDC) and measurement method uncertainty must be sufficient to meet measurement quality objectives to both quantify the average concentration of the radioactive material and to identify areas of elevated activity. In addition, scanning equipment must be coupled with global positioning system (GPS) or other locational data equipment (NRC 2020b).

GIS technicians can map captured data by using, for example, binning and color-coded isopleths to show the locations of radiological contamination. GIS technicians can also statistically analyze the data to determine the investigation level for which followup measurements are advisable. NUREG-1507, “Minimum Detectable Concentrations with Typical Radiation Survey for Instruments for Various Contaminants and Field Conditions,” Revision 1, issued August 2020 (NRC 2020a) presents concepts related to GPS/GIS-based techniques and methodologies, as well as considerations for detection efficiency calculations, background interferences, signal degradation, and other topics associated with radiation survey instrumentation. Decommissioning projects should select an investigation level *a posteriori* for postprocessed data (IL_{PP}) that best satisfies site-specific requirements (such as data quality objectives (DQOs) and regulatory approvals) (NRC 2020a).

MARSSIM, draft Revision 2, also indicates that a confidence interval can be used to evaluate a series of in situ measurements with overlapping fields of view. A one-tailed version of Chebyshev’s inequality or software (e.g., EPA’s ProUCL software (EPA 2013)) can be used to evaluate the probability of exceeding the upper bound of the gray region (UBGR) using an upper confidence limit (UCL). The use of a UCL applies to both Scenario A (where the UBGR equals the $DCGL_W$) and Scenario B (where the UBGR equals the discrimination limit). MARSSIM Section 8.5 contains details of this test. Physical validation samples are used to verify the range of measurement results, and the sampling locations can be identified through the development of z-scores as described below.

The following is an example of a simple approach (not described in MARSSIM) to develop an IL_{PP} that uses a z-score to establish acceptable false positive decision errors. In this case, the background population is assumed to be normally distributed (NRC 2020a). The z-score is calculated as follows:

$$z = \frac{X-\mu}{\sigma} \qquad \text{(Eq. 2-1)}$$

where:

X = the data point value
μ = the background population mean
σ = the background population standard deviation

In this context—

- A z-score equal to 0 represents a measurement equal to the mean counts per minute response.
- A z-score equal to +1 represents a measurement that is one standard deviation above the mean counts per minute response.
- A z-score equal to +2 represents a measurement two standard deviations above the mean response and so on.

Specifically, a decommissioning project can establish DQOs that define an IL_{PP} based on a number of standard deviations (z-score) above the mean background response and validation samples collected at these locations:

$$\text{Investigation Level (counts per minute)} = \mu + (z \times \sigma) \qquad \text{(Eq. 2-2)}$$

The first case in Appendix K to this document presents an example of this methodology with respect to the survey of stockpiled soil and the shielding of detectors with a lead wrap to reduce background levels and the related MDC.

3 DERIVED CONCENTRATION GUIDELINE LEVELS

This section describes how appropriate DCGLs can be determined for contaminants in the subsurface. Subsurface residual radioactivity exposure scenarios are different from those of surface residual radioactivity, and the approaches must be different from those used for the surface. Dose modeling and radiological surveys of the site can be integrated to provide appropriate DCGLs, including suitable possible use of multiple DCGLs for different surface and subsurface layers.

KEY POINTS

- Limited guidance is available that distinguishes between the surface DCGLw and a subsurface DCGL.
- A surface MARSSIM-based approach may be extended to subsurface problems such as excavation surfaces.
- Multiple DCGLs may be desirable depending on the radionuclides present, scenarios selected, and actual site conditions.
- A layered approach may be used for excavations in which multiple subsurface layers or strata are considered individually and then the cumulative risk from the multiple layers or strata are assessed, as described in NUREG-1757, Volume 2, Revision 2, Appendix G.
- The MARSSIM application of a “survey unit” may not directly apply to the subsurface.

Residual levels of radioactive material that correspond to allowable radiation dose standards are calculated (derived) by analysis of various pathways and scenarios (e.g., direct radiation, inhalation, ingestion) through which exposures could occur. These derived levels, known as derived concentration guideline levels (DCGLs), are presented in terms of surface or mass activity concentrations. DCGLs usually refer to average levels of radiation or radioactivity above appropriate background levels. DCGLs applicable to soil and induced activity from neutron irradiation are expressed in units of activity per unit of mass (typically, picocuries per gram (pCi/g)) (NRC 2000a). The DCGL applicable to the average concentration over a surface soil survey unit is called the $DCGL_W$. The DCGL applicable to limited areas of elevated concentrations within a surface soil survey unit is called the $DCGL_{EMC}$. Limited guidance is available that distinguishes between the surface $DCGL_W$ and a subsurface DCGL. For the intruder (e.g., well cuttings or basement excavation) scenario, the volume of contaminated soil is brought to the surface, which would require a surface $DCGL_{EMC}$. It is possible to have multiple DCGLs at a site; this situation may require an adaption of the unity rule as described below. It would always be acceptable to use a single DCGL based on the most limiting value for each radionuclide.

The difficulty of developing DCGLs is related to whether the site is considered simple or complex as defined in NUREG-1757, Volume 2, Revision 2. The technical aspects of decommissioning sites are often described as either “simple” or “complex.” The question becomes how to define these terms. Site characterization may be complex at a site, but the

FSS, after remediation, may be simple and straightforward (NRC 2006). For planning how much effort may be needed to establish DCGLs, NUREG-1757, Volume 2, Revision 2, segregates licensees into Decommissioning Groups; generally, Groups 1–3 have mostly simple technical aspects, and Groups 5–7 have mostly "complex" technical aspects. Group 4 sites, which have no initial ground water contamination, can be either simple or complex. NUREG-1757, Volume 2, provides details on how to develop DCGLs for surface soil areas or simply use the screening level tables provided if the site qualifies (NRC 2006).

NUREG-1757, Volume 2, Revision 2, Appendix G, also provides guidance for handling DCGLs for remediating post excavation. Although MARSSIM does not apply to subsurface soils, a surface MARSSIM-based approach may be extended to subsurface problems such as excavation surfaces. The survey classification of an excavation should consider whether the entire excavated area, including the floor and the sidewalls, has the same contamination potential. A strategy for development of a $DCGL_W$ may need to consider the thickness of strata, and multiple DCGLs could be developed to represent different soil intervals (NRC 2020c).

As indicated, if subsurface residual radioactivity is present, dose modeling may be conducted for both surface (if present) and subsurface soils, and DCGLs developed for each. In these cases, the MARSSIM methodology will need to be supplemented or an alternative methodology will need to be developed to demonstrate compliance with radiological criteria for license termination. For example, the subsurface layer(s) could be considered different environmental media and an SOF approach taken to demonstrate compliance as explained in NUREG-1757, Volume 2, Revision 2, Appendix G.

Information about the existence of subsurface residual radioactivity may come from either the HSA, scoping, or characterization surveys. Direct exposure, inhalation, and ingestion pathways may be important for residual radioactivity on the surface. However, if the residual radioactivity is located in subsurface soils, certain pathways may become important to dose, and subsurface soil DCGLs derived accordingly. Because the depth and thickness of residual radioactivity are correlated to dose, the modeling should reflect the actual distribution of radioactivity in the survey unit. For example, for certain radionuclides (e.g., those whose risk is dominated by the plant ingestion pathway), the thickness of residual radioactivity is strongly correlated to dose. If the modeling assumes a thinner layer of residual radioactivity than is present, then the risk could be significantly underestimated. If the modeling assumes a thicker layer of residual radioactivity than is present, then the risk could be significantly overestimated. Additionally, for some radionuclides (e.g., those whose risk is dominated by the external dose pathway), the surface concentration may drive the risk as radiation emitted from residual radioactivity located at greater depth may be attenuated in the soil column and not contribute to dose. Dose modeling can determine the sensitivity of dose to these parameters, and DCGLs must be derived for specific depths and thicknesses or for the total thickness of residual radioactivity, or for both, to ensure that dose is not underestimated (NRC 2020b).

The following is presented to establish why radon is not considered an exposure pathway. In a *Federal Register* notice (NRC 1994a), issued as a result of comments received from a radon workshop, the NRC noted that radon would not be evaluated when developing release criteria due to the ubiquitous nature of radon in the general environment, the large uncertainties in the models used to predict radon concentrations; and the inability to distinguish between naturally occurring radon and that which occurs due to licensed activities. For the standard resident farmer scenario used by the NRC staff, all of the exposure pathways should be switched on with the exception of the radon pathway (NRC 2006).

This document describes several techniques that assist with DCGL development including how to determine a scenario and applicable parameters.

3.1 SELECTION OF SCENARIO

All sites with radiologically contaminated subsurface soils must eventually opt for a site-specific analysis to determine a site-specific $DCGL_W$. Table 5.1 of NUREG-1757, Volume 2, Revision 2, compares and describes scenarios that could be default/bounding exposure scenarios, reasonably foreseeable, and less likely but plausible.[11] When realistic exposure scenarios are used to demonstrate compliance, less likely but plausible exposure scenarios should also be evaluated to risk-inform the decision. However, these less likely but plausible scenarios need not be explicitly considered for compliance (NRC 2006). NUREG-1757, Volume 2, Revision 2, Appendix J, provides guidance on development of intrusion scenarios for buried radioactivity. These exposure scenarios consider how radioactivity at depth can be brought to the surface where a potential receptor could be exposed. Once the material is brought to the surface, the exposure scenarios described in Table 5.1 would come into play.

Potential exposure scenarios include, but are not limited to, suburban resident, industrial worker, and recreationist scenarios. For these scenarios, the exposed individual usually spends less time on site, and fewer exposure pathways are usually involved than for the resident farmer scenario. For example, industrial workers usually work 8 hours a day and do not ingest meat and milk from livestock raised on site. A recreationist, such as a jogger, baseball player, or hunter, usually spends even less time on site (e.g., 2 hours a day, 3 days a week). However, an industrial worker or a recreationist may have a higher inhalation rate than a resident farmer. Table 3-2 lists the pathways that need to be considered for the resident farmer, suburban resident, industrial worker, and recreationist scenarios. Pathways not applicable to a scenario can easily be suppressed in the RESRAD-ONSITE code so that parameters related only to those suppressed pathways need not be entered (Yu et al. 2001).

NUREG-1757, Volume 2, Revision 1 (NRC 2006), provides several scenarios that licensees might consider, which are reproduced in Table 3-1.

11 When applicable, the ground water pathway should include leaching of radionuclides from the vadose zone to the saturated zone and subsequent transport.

Table 3-1 Potential Scenarios for Use in Dose Assessments

- Residential farmer (Generic screening—NUREG/CR-5512-based).
- Urban construction (contaminated soil, no suburban or agricultural uses). This scenario is meant for small urban sites cleared of all original buildings; only contaminated land and/or buried waste remains.
- Residential (a more restricted subset of the residential farmer scenario, for those urban or suburban sites where farming is not a realistic projected future use of the site).
- Recreational User (where the site is preserved for recreational uses only).
- Maintenance Worker (tied to the Recreational User scenario but involves the groundskeepers maintaining or building on the site).
- Hybrid industrial building occupancy (adds contaminated soil, building may or may not be contaminated).
- Drinking water (e.g., no onsite use of ground water; offsite impacts from the contaminated plume).

Source: NRC 2006, Appendix I

For whichever scenario is selected for a site-specific analysis, the NRC will accept models or codes that meet the criteria in NUREG-1757, Volume 2, Revision 1, Section I.5.3.1, "Generic Criteria for Selection of Codes/Models." In particular, Decontamination and Decommissioning (DandD) (Version 2.1) and the probabilistic RESRAD-ONSITE (Version 7.2) have already been reviewed and found acceptable (NRC 2020c). NUREG/CR-7267, "Default Parameter Values and Distribution in RESRAD-ONSITE V7.2, RESRAD-BUILD V3.5, and RESRAD-OFFSITE V4.0 Computer Codes," issued February 2020 (NRC 2020e), explains the various parameters, their distributions, and dose sensitivities.

Table 3-2 compares the key parameters used in the resident farmer, suburban resident, industrial worker, and recreationist scenarios. These parameters are user-changeable input parameters. NUREG/CR-7268 provides additional descriptions and extensive details on the exposure pathways to be considered (NRC 2020d).

Table 3-2 Pathways To Be Considered for the Resident Farmer, Suburban Resident, Industrial Worker, and Recreationist Scenarios

Pathways	Resident Farmer[a]	Suburban Resident[b]	Industrial Worker[c]	Recreationist[d]
External gamma exposure	Yes	Yes	Yes	Yes
Inhalation of dust	Yes	Yes	Yes	Yes
Ingestion of plant foods	Yes	Yes	Yes	Yes
Ingestion of plant foods	Yes	Yes	No	No
Ingestion of meat	Yes	No	No	Yes
Ingestion of milk	Yes	No	No	No
Ingestion of fish	Yes	No	No	Yes
Ingestion of soil	Yes	Yes	Yes	Yes
Ingestion of water	Yes	No	No	No

[a] Resident Farmer: water used for drinking, household purposes, irrigation, and livestock watering is from a local well in the area.
[b] Suburban Resident: no consumption of meat and milk obtained from site, and the water used for drinking is from offsite sources.
[c] Industrial Worker: no consumption of water or food obtained on the site. Note the EPA's industrial worker is assumed to drink water from an onsite well (EPA 1994). However, the drinking water ingestion rates for the industrial worker and resident are different.
[d] Recreationist: no consumption of food except meat (game animals) and/or fish obtained from the onsite pond, and the water used for drinking is from offsite sources.
Source: Yu et al. 2001

3.2 CONCEPTUAL MODELS AND EXPOSURE SCENARIOS

As indicated in Figure 2-1 (from NUREG/CR-7268), the initial location of radionuclides is considered to be a layer of soil assumed to be uniformly contaminated and of a constant thickness. There can be a layer of clean cover on top of the primary contamination. The primary contamination can be above the water table, it can straddle the water table, or it can be submerged with its top at the water table (Yu et al. 2020). The cover depth to the contaminated zone will probably change somewhat with each coring, and this depth should represent a conservative estimate of the average cover depth for RESRAD-ONSITE input, or an evaluation should be performed of the impact on dose of variability in cover depth. Figure 3-1 illustrates potential subsurface modeling issues of layering, which will require sophisticated software analysis tools for averaging, kriging, and volumetric considerations. Supportive technologies include ground penetrating radar (GPR), which is the only instrument capable of collecting images of buried objects in situ, both metallic and nonmetallic (e.g., plastic, glass) containers) (NRC 2000a). Figure 3-2 illustrates the capability of GPR for locating restricting clay layers below the surface; the average depth by GPR with multiple measurements is more accurate than that obtained by measurement of corings.

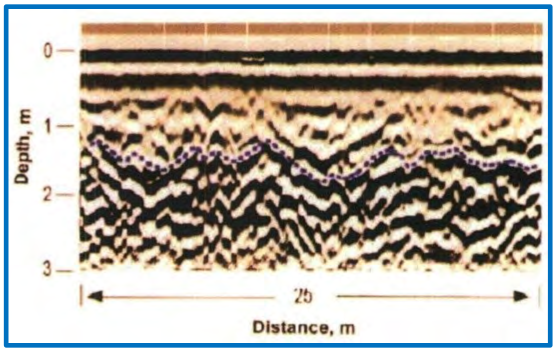

Figure 3-1 GPR Image with Subsurface Layers

Source: Pachepsky et al. 2011 (after Gish et al. 2002 (Figure 2) (Permission to use this copyrighted material is granted by John Wiley and Sons.)

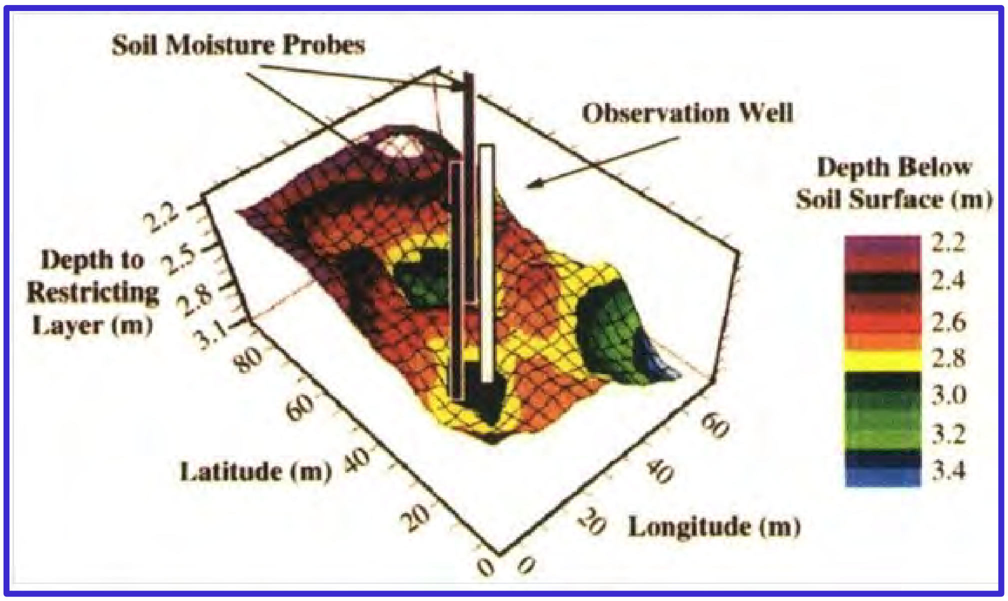

Figure 3-2 Depth to the GPR-Identified Clay Lens and Other Items

Source: Pachepsky et al. 2011 (after Gish and Kung, 2007; reprinted from *Geoderma*, Volume 138, with permission from Elsevier)

NUREG-2151, “Early Leak Detection External to Structures at Nuclear Power Plants,” issued April 2013, describes other tools for identifying changing underground conditions near NPP structures (NRC 2013a). NUREG-2151 discusses ways to provide early leak detection in the subsurface external to the structures of the facilities. Approaches to this include the use of single-point sensors to detect changes in moisture content in the vadose zone. These methods sense moisture or other parameters that may be related to leaks, such as changes in conductivity/resistivity, permittivity, or temperature. Other techniques include detection of tritium in soil vapor and temperature changes using coaxial cables (NRC 2013a).

While it would always be acceptable to select the most limiting DCGL, multiple DCGLs may be desirable depending on the radionuclides present, the scenarios selected, and the actual site conditions. These may be additive depending on the scenarios described below. Most cases will require DCGL evaluations for "as is" conditions and the intrusion scenarios for a basement excavation. Any left-behind contaminated basement scenarios may also require independent DCGL evaluations of the partial basement excavations and well drilling.

3.3 CONCEPTS FOR BURIED MATERIAL

NUREG-1757, Volume 2, presents several scenarios for buried materials:

- basement excavation (residual radioactivity within 3 m of the surface considering erosion) and other scenarios if residual radioactivity is found deeper in the subsurface (e.g., well drilling)

- guidance on scenarios is also included for large backfilled subgrade structures (e.g., containment basements, auxiliary building basements, and/or turbine basements at a reactor site) including large-scale excavations

The dose to the construction worker, disposal facility worker, or other member of the public who may be exposed to the residual radioactivity on the excavated concrete and/or fill material needs to be considered. Note that NUREG-1757, Volume 2, Revision 2, considers mixing of "contaminated" soil with the "clean" cover and any additional clean material below the surface as acceptable for dose modeling. The guidance indicates adding dose from "as is" to dose from any intrusions (e.g., drill cuttings and excavations).

The radionuclide concentrations (becquerels per kilogram (Bq/kg) or pCi/g) in the excavated concrete are directly related to the ratio of concrete surface area to concrete/soil volume excavated. For substructures that have thick walls and for which the contamination is limited to the structure surface, assuming a partial excavation that includes only the walls with the minimum thickness would result in a higher concentration (NRC 2020c).

As noted in NUREG-1757, Volume 2, Revision 2, Appendix G, a layered approach may be used for excavations in which multiple subsurface layers or strata are considered individually and then the cumulative risk from the multiple layers or strata are assessed. For example, surface soil is important to the external dose and inhalation pathways, intermediate depth soil corresponding to the till depth is potentially important to the plant ingestion pathway, and subsurface soil may be important to the ground water pathway. In cases where different sets of DCGLs are developed for different strata, it is important to ensure that the average contaminant concentration in each designated stratum is lower than the applicable DCGL and that any elevated areas are appropriately investigated and addressed. An SOF approach can be used to assess the cumulative risk associated with multiple strata. NUREG-1757, Volume 2, Revision 2, Appendix G, provides details. Of course, intrusion scenarios, as described above for the basement excavation scenario, are to be considered to develop subsurface DCGLs for otherwise inaccessible subsurface soils at depth (NRC 2020c).

NUREG-1757, Volume 2, Appendix J, provides a model for assessing buried material, which, with slight modifications, is also appropriate for any subsurface contamination. As described, a conservative analysis could assume two exposure scenarios: (1) leaching of the radionuclides from their current subsurface location or buried position to the ground water, which is then used by a residential farmer, and (2) inadvertent intrusion into the buried or subsurface residual radioactivity by house construction for a resident farmer, with the displaced soil, which includes part of the residual radioactivity, spread across the surface (Figure 3-3). The second alternative exposure scenario encompasses all the exposure pathways and, although not all of the source term is in the original position, leaching will occur from both the remaining buried residual radioactivity (if there is any) and the surface soil (NRC 2020c).

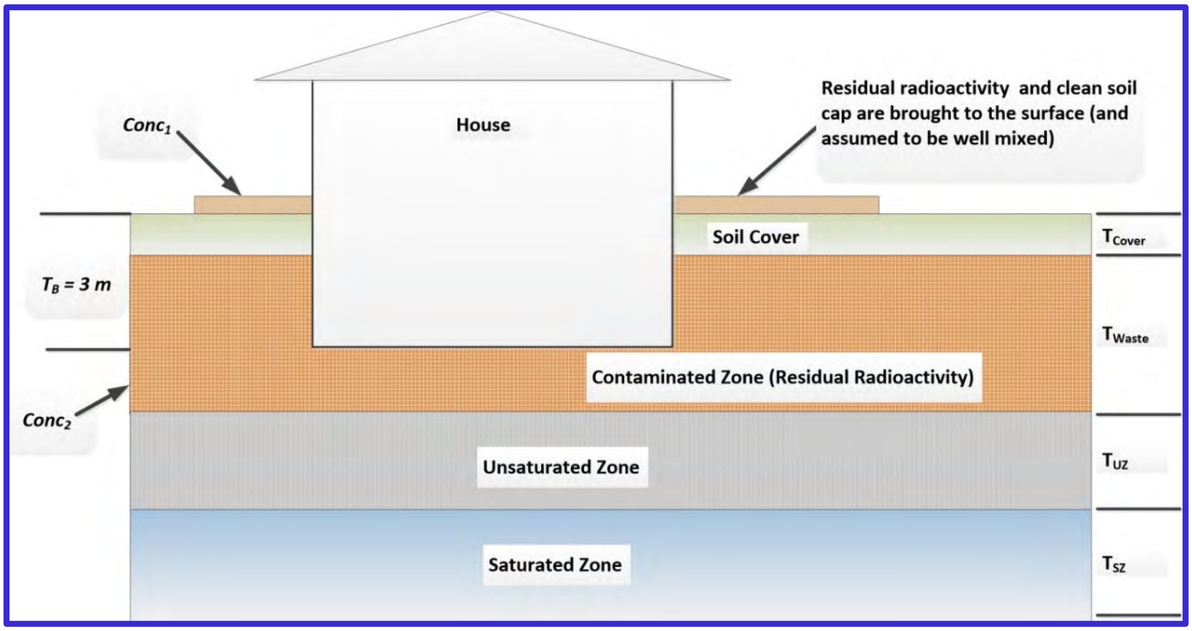

Figure 3-3 Conceptual Buried Disposal Problem

Source: Modified from NRC 2020c, Appendix J

Figure 3-4 shows an interpretation of the NRC's buried waste depiction. This illustration shows how mixing could occur if only one contaminated cell (bottom cell) were excavated with two other uncontaminated cells (Lively 2012).

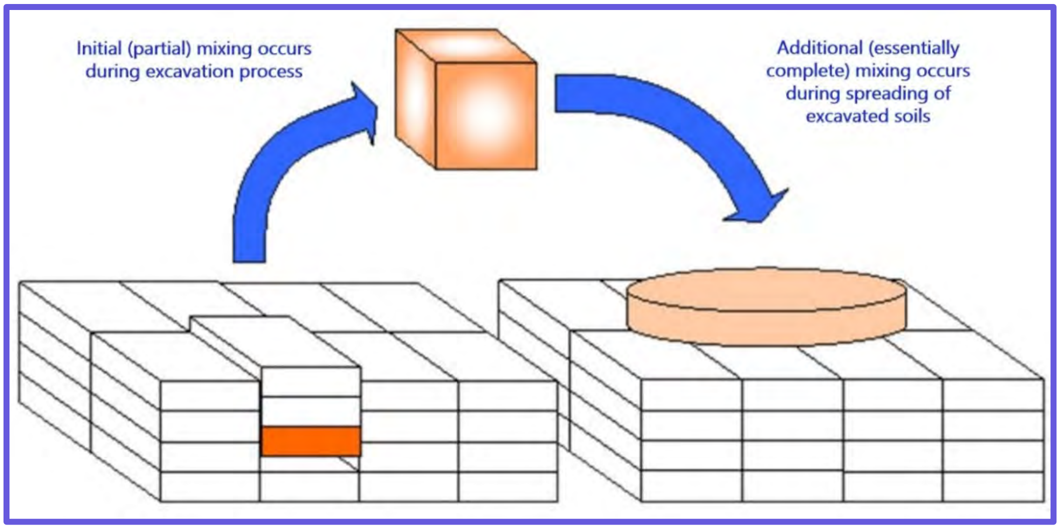

Figure 3-4 Conceptual Mixing Volume Mode

Source: Lively 2012 (Copyright © by WM Symposia. All Rights Reserved. Reprinted with permission.)

3.4 DEVELOPMENT OF DERIVED CONCENTRATION GUIDELINE LEVELS

Argonne National Laboratory (ANL) developed the RESRAD computer code for the DOE to calculate site-specific residual radiation guidelines and radiation dose to future hypothetical onsite individuals at sites contaminated with residual radioactive material. The DOE adopted the RESRAD-ONSITE code in Order 5400.5, "Radiation Protection of the Public and the Environment," issued January 1993 (DOE 1993), for derivation of soil cleanup criteria and dose calculations, and it is widely used by the DOE, other Federal agencies, and industry. The NRC describes use of both DandD and RESRAD-ONSITE in NUREG-1757, Volume 2.

The RESRAD family of codes has an assumed conceptual model; therefore, the analyst must determine only if the assumed conceptual model is appropriate for the problem. However, unlike DandD, the RESRAD family of codes do not have prescribed exposure scenarios. The analyst develops the exposure scenario by switching on or off various exposure pathways or adjusting parameters. For the standard resident farmer exposure scenario commonly used by the NRC staff, all the exposure pathways should be switched on for unrestricted use cases, with the exception of the radon pathway. The analyst should justify excluding any of the other pathways. For example, if it can be shown that the ground water at the site cannot be used because of either poor ambient water quality (e.g., salinity) or low yields, the elimination of the ground water pathway may be justified. A finding that the ground water is unsuitable is typically made in coordination with State agencies. For more information on eliminating pathways, see NUREG-1757, Volume 2, Appendices I and M.

The RESRAD family of codes requires that the radioactive inventory be input as a source concentration. Because the codes are designed for conducting site-specific analyses, it is expected that, for most analyses, the analyst will have data on radionuclide concentrations at the site. It should be appropriate to use the arithmetic average of the radionuclide concentration in the analysis (note that this also includes any interspersing clean soil). The RESRAD-ONSITE and RESRAD-OFFSITE codes allow the user to input information on the area and thickness of the residual radioactivity (i.e., these are not fixed, although defaults are provided). For surface residual radioactivity (≤0.9 m (3 feet), which is the default root depth), the site-specific mean concentration, area of residual radioactivity, and thickness of the residual radioactivity can be input directly in the code. For deeper residual radioactivity, or if the residual radioactivity is capped (such as with burials), assumptions should be made about how much waste may be brought to the surface and how it may be mixed with uncontaminated soil (NRC 2020e).

3.5 THE UNITY RULE

Most of the scenarios discussed in this document will require one or more DCGLs. Typically, each radionuclide DCGL corresponds to the release criterion. However, in the presence of multiple radionuclides (or multiple layers), the total of the DCGLs for all radionuclides would exceed the release criterion. The unity rule is used to adjust the individual radionuclide DCGLs. The unity rule, represented in the expression below, is satisfied when radionuclide mixtures yield a combined fractional concentration limit that is less than or equal to 1:

$$\frac{C_1}{DCGL_1} + \frac{C_2}{DCGL_2} + \cdots \frac{C_n}{DCGL_n} \leq 1 \tag{3-1}$$

where:

C_i = concentration
$DCGL_i$ = guideline value for each individual radionuclide (1, 2, ..., n).

To perform the elevated measurement comparison (EMC), the size of the area in the survey unit with a concentration greater than the $DCGL_W$ is determined, then the $DCGL_{EMC}$ for an area of that size is determined. (The EMC is used to demonstrate compliance for small areas of elevated activity.) The average concentration in the area is also determined. The EMC is acceptable if the following condition is met (MARSSIM Equation 8-2) (NRC 2000a):

$$\frac{\delta}{DCGL_W} + \frac{\overline{C_{EA}} - \delta}{DCGL_{EMC}} \leq 1 \tag{3-2}$$

where:

δ = the average residual radioactivity concentration for all sample points in the survey unit that are outside the elevated area,
$\overline{C_{EA}}$ = the average concentration in the elevated area, and
$DCGL_{EMC}$ = cleanup level for smaller, elevated area.

If there is more than one elevated area, a separate $DCGL_{EMC}$ term should be included for each.

In many cases (see Section 10), licensees have used a layered approach in which multiple subsurface layers or strata are considered individually and then the cumulative risk from the multiple layers or strata are assessed. If the sidewalls of the excavation are combined in the same Class 1 survey unit with the bottom of the excavation, then the cumulative risk from all of the strata (below and above the bottom of the excavation) should be considered.

As noted, in some cases, multiple sets of DCGLs may have been approved for different strata or layers below final grade based on dose modeling. For example, surface soil is important to the external dose and inhalation pathways, intermediate depth soil corresponding to the till depth is potentially important to the plant ingestion pathway, and subsurface soil may be important to the ground water pathway. Intrusion scenarios are considered to develop subsurface DCGLs for otherwise inaccessible subsurface soils at depth (see NUREG 1757, Volume 2, Appendix J). In cases where different sets of DCGLs are developed for different strata, it is important to ensure that the average contaminant concentration in each designated stratum is lower than the applicable DCGL and that any elevated areas are appropriately investigated and addressed. An SOF approach can be used to assess the cumulative risk associated with multiple strata. For example, an SOF approach may entail calculating the SOF for each sampling location considering the entire soil column, and then calculating the average SOF for all the locations if the SOF is greater than 1 for any one location, or evaluating the SOF for multiple strata using the average concentration for each stratum. In all cases, it is important to understand the basis for development of the DCGLs (thickness, depth, distribution, and area of residual radioactivity) for each stratum to ensure that risk is not underestimated. It is also important to understand the dose modeling assumptions about the reuse of soils in the excavation (i.e., use of clean or slightly contaminated soils) to ensure that the risk is not underestimated. In complex cases involving subsurface residual radioactivity, it is always prudent to calculate the final estimated dose for the compliance scenario(s) based on the final configuration and measured radionuclide concentrations of residual radioactivity at the site through dose modeling.[12]

If there are surface and subsurface DCGLs, then the unity rule represented in the expression below, is satisfied when radionuclide mixtures yield a combined fractional concentration limit that is less than or equal to 1:

$$\left(\frac{\delta}{DCGL_w} + \frac{\overline{C_{\cdot EA}} - \delta}{DCGL_{EMC}}\right) + \sum_1^n \frac{C_i}{DCGL_{V_i}} \leq 1 \qquad (3\text{-}3)$$

where:

$DCGL_{V_i}$ = volumetric guideline value for each individual radionuclide (1, 2, ..., n).

For sites that have a number of significant radionuclides, a higher sensitivity is desired in the measurement methods as the values of $DCGLv_i$ become smaller. Also, this is likely to affect statistical testing considerations—specifically, by increasing the numbers of data points necessary for statistical tests (NRC 2000a).

3.6 COMPUTER CODES ACCEPTABLE TO THE NRC FOR DOSE ASSESSMENT

A brief introduction to the computer codes acceptable to the NRC that address compliance with the dose criteria of 10 CFR Part 20, Subpart E, follows.

3.6.1 DandD Code

The DandD software package, developed by the NRC, addresses compliance with the dose criteria of 10 CFR Part 20, Subpart E. Specifically, DandD embodies the NRC's guidance on screening dose assessments to allow licensees to make simple estimates of the annual dose from residual radioactivity in soils and on building surfaces. The DandD software automates the definition and development of the scenarios, exposure pathways, models, mathematical

12 Although commonly used codes such as RESRAD-ONSITE consider only one average soil concentration as input to the code, the code can be run multiple times and the doses summed to assess the contributions of multiple strata.

formulations, assumptions, and justifications of parameter selections documented in Volumes 1 and 3 of NUREG/CR-5512 (NRC 1992; NRC 1999). The code is available through registration at https://ramp.nrc-gateway.gov.

Figure 3-5 presents the pathway exposure selection screen for a residential scenario from DandD. Figure 3-6 shows the DandD box model for the drinking water scenario (note that the default value for the thickness, H1, is 15 cm).

Figure 3-5 DandD Exposure Pathway Selection Screen

Source: NRC 2001a

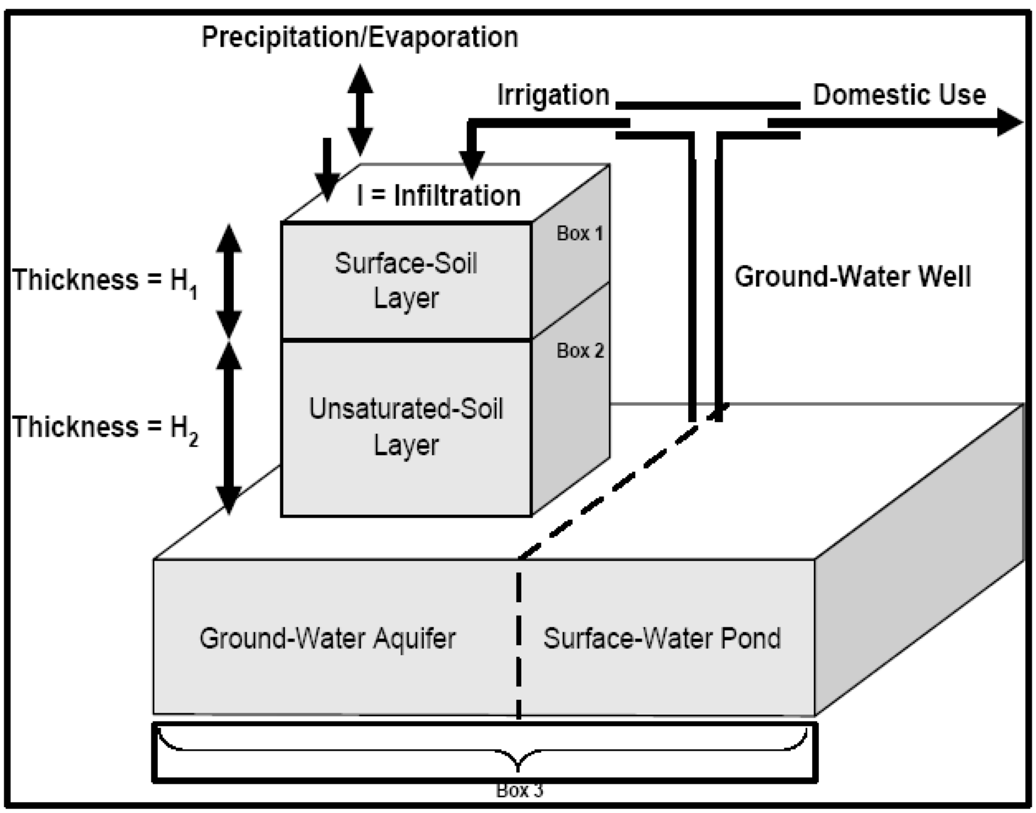

Figure 3-6 DandD Code Simple Models for Screening Analysis

Source: NRC 1992

3.6.2 RESRAD-ONSITE Code

The RESRAD 7.2 code for site-specific modeling applications was adapted by ANL for NRC regulatory applications for probabilistic dose analysis to demonstrate compliance with the NRC's LTR (10 CFR Part 20, Subpart E) according to the guidance developed for NUREG-1727, “NMSS Decommissioning Standard Review Plan,” issued September 2000 (NRC 2000b). The code is available through registration at https://resrad.evs.anl.gov/download/.

RESRAD can be used for analyzing the resident farmer scenario and others. As with the generic conceptual models used by DandD for analyzing the resident farmer scenario, the conceptual models in RESRAD (see Figure 3-7) are complex. RESRAD models external exposure from volume soil sources when the person is outside, using volume dose rate factors from Federal Guidance Report (FGR) No. 12, “External Exposure to Radionuclides in Air, Water, and Soil,” issued September 1993 (Eckerman and Ryman 1993). Correction factors are used to account for soil density, areal extent of residual radioactivity, thickness of residual radioactivity, and cover attenuation. When the person is indoors, exposure from external radiation is modeled in a similar manner except that additional attenuation is included to account for the building. Exposure through ingestion of contaminated animal and plant products is modeled simply through the use of transfer factors. Licensees may request an exemption from 10 CFR Part 20 to use the latest dose conversion factors (e.g., International Commission on Radiological Protection (ICRP) 72, “Age-Dependent Doses to the Members of the Public from Intake of Radionuclides,” issued 1996 (ICRP 1996)). Scenarios and critical group assumptions should be revisited to look at age-based considerations. Licensees may not “pick and choose” dosimetry methods for radionuclides (e.g., FGR No. 11, “Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion,” issued September 1988 (Eckerman et al.1988)) (NRC 2006).

The generic source-term conceptual model in RESRAD assumes a time-varying release rate of radionuclides into the water and air pathways. Radionuclides in the contaminant zone are assumed to be uniformly distributed. No transport is assumed to occur within the source zone, but RESRAD does account for radioactive decay. In terms of containment, the radioactive material is not assumed to be contained (or containers are assumed to have failed). RESRAD does allow inclusion of a cover over the contaminated area. However, the cover is not assumed to limit infiltration of water and is assumed to function only in terms of providing shielding from gamma radiation. Release of radionuclides by water is assumed to be a function of a constant infiltration rate, time-varying contaminant zone thickness, constant moisture content, and equilibrium adsorption. The contaminant zone is assumed to decrease over time from a constant erosion rate. RESRAD assumes a uniform release of tritium and carbon-14 gases, based on a constant erosion loss rate. Particulates are assumed to be instantaneously and uniformly released into the air as a function of the concentration of particulates in the air, based on a constant mass loading rate. Figure 3-7 shows the pathways evaluated in RESRAD (NRC 2006).

The median of the national distribution of the depth to top of aquifer is 48.55 m and follows a lognormal distribution. The RESRAD model adopted a default value of 10 m for the well-pump intake depth (Yu et al. 2015).

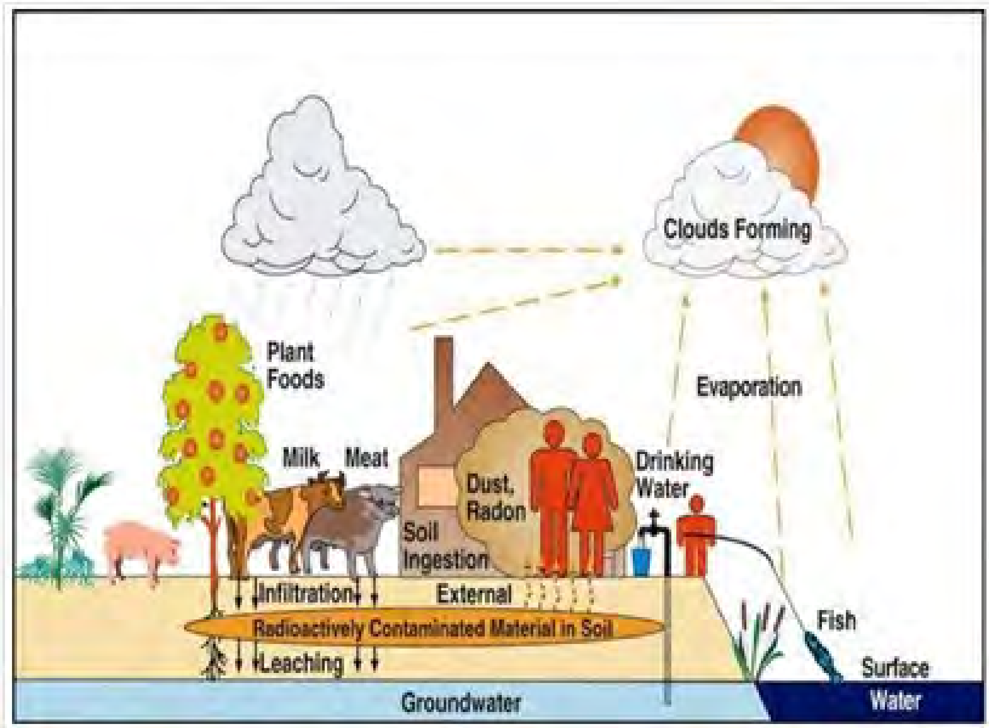

Figure 3-7 Conceptual Model for RESRAD Resident Farmer

Source: Yu 2012

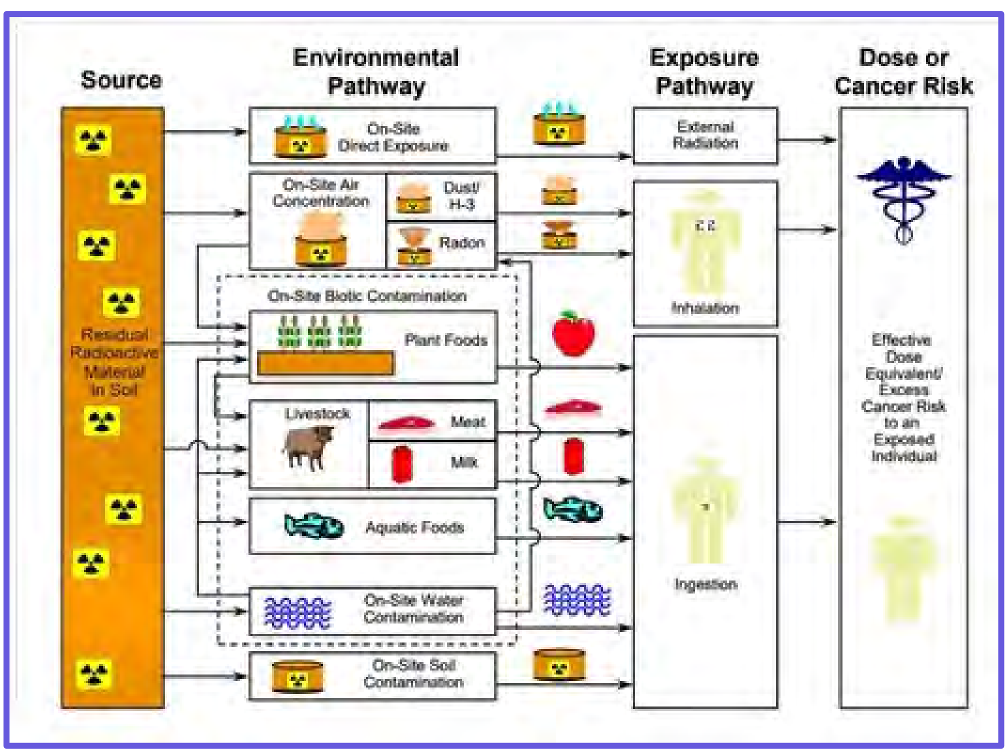

Figure 3-8 Allowable Pathways Used in RESRAD

Source: Yu et al. 2001

Site-specific parameters should be used whenever possible, especially for results sensitive to parameter values (Yu et al. 2015). Each licensee will decide on site-specific parameters. At reactor and other complex sites, successful DCGL development required use of sophisticated mathematical tools such as GIS, modeling software for environmental issues and doses, subsurface kriging software, and various subject matter experts (e.g., geologists, core drilling experts, certified health physicists, GIS experts, hydrogeologists, safety experts, and chemists).

The presence of solvents or other volatile chemicals that affect the ion-exchange capacity of soil can enhance radionuclide mobility. MARSSIM considers only radiation-derived hazards and does not deal with any hazards posed by chemical contamination (NRC 2000a). If solvents or other volatile chemicals are an issue, the appropriate regulator (the State, EPA, or both) should be included in early discussions.

3.6.3 RESRAD-OFFSITE Code

RESRAD-OFFSITE extends RESRAD-ONSITE to offsite locations. In addition to more complex air and ground water models, RESRAD-OFFSITE can handle more complex source terms and waste forms. The calculation of dose and cancer risk is scenario driven, by activating exposure pathways and using parameter values commensurate with the scenario under consideration. As in RESRAD-ONSITE, nine exposure pathways are modeled as shown in Figure 3-9. They include external radiation, inhalation of airborne radionuclides, ingestion of plant foods, meat, milk, water, and aquatic food, incidental ingestion of soil, and inhalation of radon (NRC 2020d). The NRC sponsored development of this code in the areas of source term and surface water modeling. As this is a new code, it does not yet have the experience base of RESRAD-ONSITE. The code is available through registration at https://resrad.evs.anl.gov/download/.

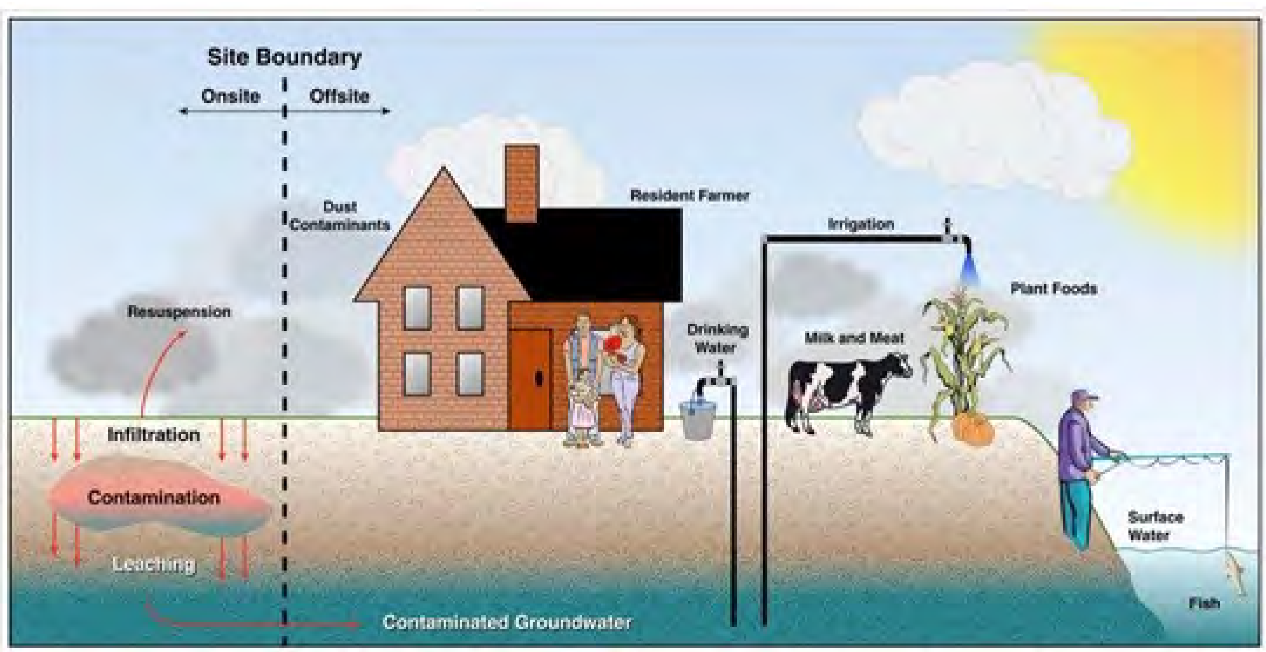

Figure 3-9 RESRAD-OFFSITE—Extending the Analysis Beyond the Contaminated Sites

Source: NRC 2020d

Unlike RESRAD-ONSITE, which assumes the residence and agricultural fields are collocated with the primary contamination, RESRAD-OFFSITE allows them to be at different locations, each at a specific distance and direction from the primary contamination, and to have specific dimensions. The same option extends to a well and a surface water body, which can be off the centerline of the ground water flow direction. Accumulation of radionuclides because of air deposition and irrigation at offsite locations is also modeled, contributing to radiation exposures of the receptor (NRC 2020d).

RESRAD-OFFSITE incorporates a Gaussian plume model based on area source release to calculate air concentrations at offsite locations. For ground water transport modeling, in addition to radiological decay and ingrowth, advection, and sorption and desorption between solid and liquid phases in soil, one-dimensional and three-dimensional dispersion are also considered for the unsaturated zones and saturated zone, respectively, and the transport extends beyond the boundary of the primary contamination (NRC 2020d).

3.6.4 Incompatible Site Features and Conditions

NUREG-1757, Volume 2, Revision 2, lists site features that may be incompatible with DandD and RESRAD-ONSITE. Table 3-3 and Table 3-4, respectively, present these features.

Table 3-3 Site Features and Conditions that May Be Incompatible with Those Assumed in DandD

- sites with highly heterogeneous radioactivity
- sites with wastes other than soils (e.g., slags and equipment)
- sites that have multiple source areas
- sites that have contaminated zones thicker than 15 cm (6 inches)
- sites with chemicals or a chemical environment that could facilitate radionuclide releases (e.g., colloids)
- sites with soils that have preferential flow conditions that could lead to enhanced infiltration
- sites with a perched water table, surface ponding, or no unsaturated zone
- sites where the ground water discharges to springs or surface seeps
- sites with existing ground water contamination
- sites where the potential ground water use is not expected to be located immediately below the contaminated zone
- sites with significant transient flow conditions
- sites with significant heterogeneity in subsurface properties
- sites with fractured or karst formations
- sites where the ground water dilution would be less than 2,000 m^3 (70,000 ft^3)
- sites where the overland transport of contaminants is of potential concern
- sites with radionuclides in soil that may generate gases (i.e., H-3 or C-14)
- sites with stacks or other features that could transport radionuclides to result in a higher concentration off site than on site

Source: NRC 2020c

Table 3-4 Site Features and Conditions that May Be Incompatible with Those Assumed in RESRAD-ONSITE

- sites with highly heterogeneous radioactivity
- sites with wastes other than soils (e.g., slags and equipment)
- sites with multiple source areas
- sites that have chemicals or a chemical environment that could facilitate radionuclide releases
- sites with soils that have preferential flow conditions that could lead to enhanced infiltration
- sites where the ground water discharges to springs or surface seeps
- sites where the potential ground water use is not expected to be located in the immediate vicinity of the contaminated zone
- sites with significant transient flow conditions
- sites with significant heterogeneity in subsurface properties
- sites with fractured or karst formations
- sites where overland transport of contaminants is of potential concern
- sites with stacks or other features that could transport radionuclides off the site at a higher concentration than on the site

Source: NRC 2020c

3.7 POTENTIAL PATHWAYS

Figure 3-7 above illustrates the major pathways used to derive site-specific soil guidelines in the RESRAD code. Minor pathways for onsite exposure are not considered in deriving soil guidelines because the dose contribution from these pathways is expected to be insignificant. External radiation from a surface layer formed by redeposition of airborne radionuclides carried by the wind from an exposed contaminated zone is expected to be insignificant compared with external radiation from the residual radioactive material in its original location. External radiation from contaminated water is expected to be insignificant compared with internal exposure from radionuclides ingested in drinking water. The external radiation dose from airborne dust is much smaller than the inhalation dose from dust (by a factor of 100 or more for radionuclides in the uranium-238 series. The external radiation dose from airborne radon decay products is negligible compared with (1) the internal inhalation dose to the lungs, (2) the external radiation dose from the parent radium in the soil, or (3) the internal radiation dose from ingestion of plant foods grown in the radium-contaminated soil. Transport and dosimetry for gaseous airborne radionuclides other than radon decay products (e.g., carbon-14 occurring in carbon dioxide or tritium occurring in tritiated water vapor) require special consideration (Yu et al. 2001).

Fortunately, both DandD and RESRAD-ONSITE software codes have multiple published documents exploring potential pathways. RESRAD-ONSITE is generally accepted by industry as the go-to software as it is also supported with training manuals and user guides.

Many of the subsurface scenarios discussed above include an intrusion scenario that involves a resident farmer. Fortunately, NUREG/CR-7267 presents an analysis of important exposure pathways for 12 selected radionuclides in the resident farmer scenario, which illustrates the relative importance of the pathways. NUREG/CR-7267 also provides tables showing which parameters are sensitive to dose and also a listing of peak dose times (NRC. 2020e).

3.8 SITE-SPECIFIC PARAMETER SELECTION PROCESS

Documenting why site-specific parameters were selected to run RESRAD can be exhausting. Justification must be provided as to why or why not a parameter was selected even if using a default value. NUREG/CR-7267 (Kamboj et al. 2020) is an excellent document to review for understanding the various parameters that can or should be changed and documenting use of any parameter. Also, it is important to note that the default metabolic and behavioral parameters in DandD (and documented in NUREG/CR-5512, Volume 3) can be used with limited justification consistent with the default exposure scenarios. NUREG-1757, Volume 2, Revision 2, Table I.11, lists most of these parameters (NRC 2020c).

3.9 IMPLICATIONS OF CONTAMINATED WATER RELEASES

A series of uncontrolled releases of radionuclides (principally tritium) to the subsurface at commercial NPPs has occurred over the past decade or so. These releases originated from nuclear plant structures, systems, and components that store or convey liquids and gases containing radionuclides; and leaks from spent fuel pools, vacuum breakers, pipes within concrete pipe vaults, buried pipes, and condensate storage tanks. Although the radionuclides released from these underground leaks primarily consisted of tritium, the contamination often included a variety of radionuclides unique to each plant (Nicholson et al. 2011).

Site-specific simulations are encouraged in the scoping and characterization phases, even if limited data on water concentrations are available, to obtain preliminary DCGLs as a base for survey instrument selection and measurement methods. An exposure scenario for radioactive material leaching into ground water is part of the software simulation; concentrations must be entered if they exist, as well as the probable number of years since the material was placed.

Additionally, as the permissible DCGL for subsurface soil volumes ($DCGL_V$) rises because of site-specific scenarios including that for the resident farmer, offsite doses may also increase, primarily through the water-dependent pathway, as indicated in Figure 3-10 (Yu et al. 2001).[13] The $DCGL_V$ for onsite and offsite scenarios must be considered to ensure that the dose limits in 10 CFR Part 20, Section E, are met.

13 The “User’s Manual for RESRAD Version 6,” Section 2, explains Figure 3-10 (Yu et al. 2001).

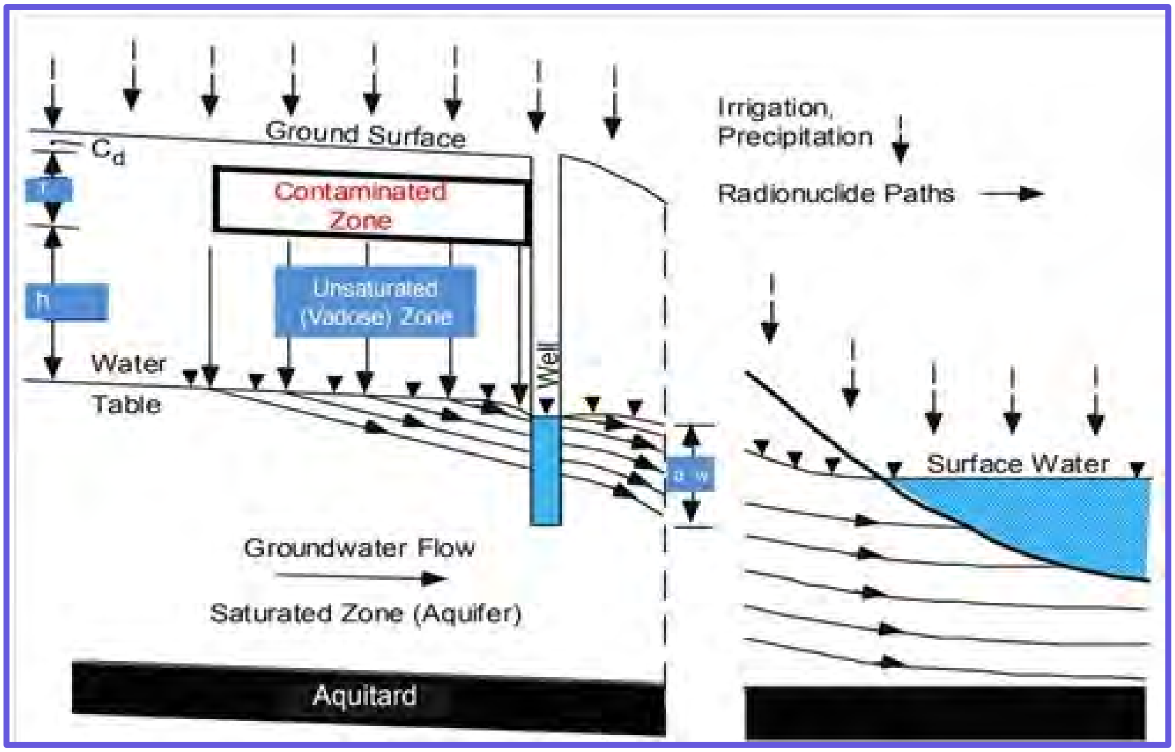

Figure 3-10 Schematic Representation of the Water Pathway Segments

Source: Yu et al. 2001

3.10 ESTIMATES OF SITE PHYSICAL PARAMETERS

Several parameters for source characteristics must be understood to perform an initial assessment. Estimates for parameters such as the area of the contaminated zone, cover depth, depth of the contamination zone, depth to the water table, any water contamination, and time of radionuclide placement are required inputs for RESRAD-ONSITE.

4 IMPLICATIONS OF NUREG-1757, VOLUME 2

NUREG-1757, Volume 2, Revision 2 (NRC 2020c), is the leading NRC guidance on methods to develop quantitative cleanup criteria ($DCGL_W$ and $DCGL_{EMC}$); material in this section will aid in deciding if the guidance needs to be supplemented. For example, given the relative importance of the ground water pathway and intrusion scenarios for subsurface residual radioactivity, how does the importance of smaller areas of residual radioactivity in the subsurface differ from the surface?

KEY POINTS

- Water-dependent pathways are explained.
- Classification of soil by the U.S. Department of Agriculture (USDA) is illustrated.
- Primary references for definition of RESRAD parameters are discussed.
- Subsurface survey units do not necessarily match up with surface survey units.
- How small a *hot spot* can be estimated? Guidance is needed as to how large a soil volume concentration may be averaged over to meet a DCGL—just the hot spot or the entire facility acreage, or just the restricted area? Can analysis relate MARSSIM surface areas to the subsurface?

The largest contribution from the ground water pathway is for drinking water from the unconfined aquifer tapped by a well at the downgradient boundary of the contaminated area. For most NRC licensees, ground water dose is calculated for onsite receptors using the RESRAD-ONSITE computer code. The ground water dose contribution can be similar for onsite and near-site residents but decreases for wells at greater distances from the boundary (Yu et al. 2001).

This section explores the importance of (1) the effect of distance between a contaminated layer and the water table on dose, (2) approaches to subsurface assessments, (3) categorization and classification of subsurface soils, and (4) the importance of smaller areas of residual radioactivity in the subsurface.

4.1 WATER-DEPENDENT PATHWAYS

The “User’s Manual for RESRAD Version 6” explains important subsurface physical parameters and how to measure them (Yu et al. 2001). The manual also provides information about the contribution from water-dependent pathways that may be delayed until radionuclides transported by ground water reach a point of water withdrawal (i.e., a well or pond).[14] The time dependence of these pathways is discussed in terms of the hydrological model used for the ground water pathway segment (Yu et al. 2001). As a fairly new publication in 2020, NUREG/CR-7267 provides an update and even more detailed explanations of water-dependent

[14] This assumes that the radioactivity must be transported to the water table, that the nondispersion model in RESRAD is used, or both.

pathways; concerns about nondispersion or mass balance models and time dependence are also discussed there (NRC 2020e).

4.2 RESRAD SIMULATIONS

The RESRAD-ONSITE code has 130 radionuclide-independent parameters, 10 radionuclide-dependent parameters, and 5 element-dependent parameters. The parameters were classified into three types: physical, behavioral, and metabolic (NRC 2020e).

NUREG/CR-7268 provides updated information on the default parameter values and parameter distributions contained in the RESRAD family of codes since the release of the probabilistic RESRAD-ONSITE Version 6.0 (formerly called RESRAD 6.0), RESRAD-OFFSITE Version 2.0, and RESRAD-BUILD Version 3.0 (Yu et al. 2012). This report also discusses certain changes made in the family of RESRAD codes since 2002. All three codes are pathway analysis models designed to evaluate the potential radiological dose incurred by an individual who lives at a site with radioactively contaminated soil or who works in a building containing residual radioactive material (NRC 2020e). The document describes in detail the various parameters and their importance; however, site-specific parameters are necessary and required (use of any default parameter must be justified as described in NUREG-1757, Volume 2, Revision 1 (NRC 2006).

4.3 CATEGORIZATION AND CLASSIFICATION OF SOIL

4.3.1 Soil Definition

MARSSIM defines soil as the top layer of the earth's surface, consisting of rock and mineral particles mixed with organic matter. This definition may lead to confusion as some site managers may want large rocks to be permitted in samples for dilution of the actual soil concentration. Further, MARSAME as a supplement to MARSSIM does not provide an exact definition of the transition between surficial and volumetric radioactive material (NRC 2009a). This white paper proposes a clearer explanation of what should be considered for soil samples and their contents, as well as information relevant to identifying subsurface layers.

The soil referred to in this document encompasses the mass (surface and subsurface) of the unconsolidated mantle of weathered rock and loose material lying above solid rock. Further, a distinction must be made as to what fraction of the unconsolidated material is soil and what fraction is not. The soil component here is defined as all mineral and naturally occurring organic material that is 2 millimeters (mm) (0.8 inches) or less in size. This is the size normally used to distinguish between soils (consisting of sands, silts, and clays) and gravels. In addition, the 2-mm (0.8-inch) size is generally compatible with analytical laboratory methods, capabilities, and requirements (EPA 1990). Figure 4-1 presents the particle sizing for soil; beyond the 2-mm (0.8-inch) size, it is considered gravel, not soil.

Figure 4-1 Soil Particle Sizing Chart

Source: EPA 2000

Figure 4-2 depicts the USDA soil texture classification chart.

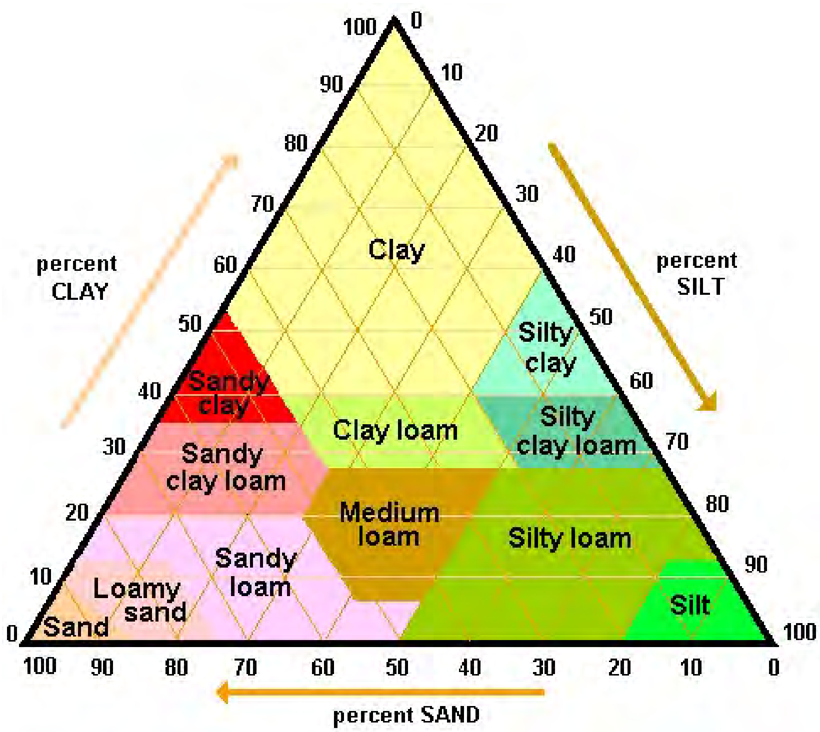

Figure 4-2 U.S. Department of Agriculture Soil Texture Classification

Source: EPA 2000

In most situations, the vegetative cover is not considered part of the surface soil sample and is removed in the field. For agricultural scenarios where external exposure is not the primary concern, soil particles greater than 2 mm (0.08 inches) are generally not considered as part of the sample. Foreign material (e.g., plant roots, glass, metal, or concrete) is also generally not considered part of the sample, but should be reviewed on a site-specific basis. It is important that the sample collection procedure clearly indicate what is and what is not considered part of the sample (EPA 1990).

4.3.2 Categorization

Following MARSAME (NRC 2009a) guidance, the term “categorization” is used to describe the decision as to whether subsurface soils are impacted or nonimpacted. The term “nonimpacted” applies to subsurface soil-like material where there is no reasonable potential to contain radionuclide concentration(s) or radioactivity above background. “Impacted” applies to subsurface soil-like material that is not classified as nonimpacted.

The next section describes potential decision areas and volumes.

4.4 IDENTIFICATION OF SURVEY DECISION AREAS AND VOLUMES

MARSSIM is a surficial survey document, but its philosophy can be partially applied to subsurface volumes. There should be an initial site-specific RESRAD simulation to establish the water-dependent dose from the contamination. The water-dependent dose is then added to a second RESRAD simulation for the inadvertent intruder scenario (e.g., well drill cuttings, excavated basement, or buried radioactive material) discussed in Section 3.

As shown in Figure 4-3, a contaminant source may be under two or several surface area survey units. Note that the EPA’s 0.5-acre exposure area is about the same size as a MARSSIM Class 1 survey unit. (See Figure 4-3.)

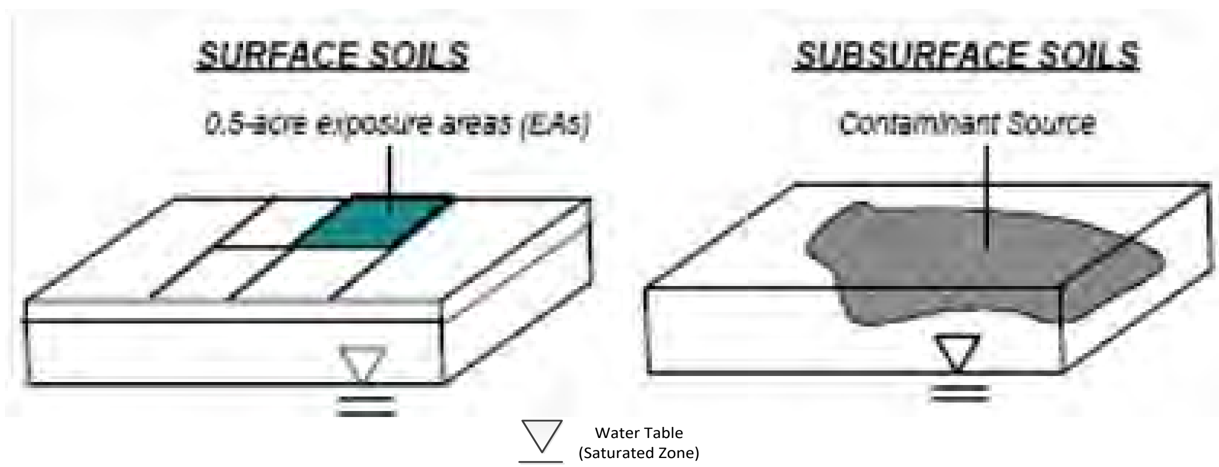

Figure 4-3 Illustration of Surface Soil Exposure Areas and Subsurface Contaminate

Source: EPA 2000

Following categorization, the impacted volumes might be classified similarly to those in MARSSIM, which provides a graded approach as to allocation of resources for survey design.

MARSSIM requires that a survey unit not include areas that have different classifications, but how to accomplish this in the subsurface is not yet clear. However, the survey unit’s characteristics should be generally consistent with exposure pathway modeling used to convert dose or risk into radionuclide concentrations. Sizes or volumes for subsurface soil survey units are not yet defined following the MARSSIM Class 1, 2, and 3 surface soil survey units.
Table 4-1 presents the recommended survey unit sizes for surface areas taken from MARSSIM and NUREG-1757, Volume 2, Revision 2.

Table 4-1 Suggested Survey Unit Surface Area

Classification	Surface Area
Class I	2,000 m^2
Class II	2,000 to 10,000 m^2
Class III	No limit

Source: NRC 2000a

4.5 IMPORTANCE OF SMALLER AREAS OF RESIDUAL RADIOACTIVITY IN THE SUBSURFACE

4.5.1 Intrusion

With intrusion into a buried fill or excavation of a contaminated layer below the surface, the material is assumed to be brought to the surface where the routine RESRAD considerations take over for development of DCGLs. The contaminated and uncontaminated volumes that may be brought to the surface may be estimated through kriging, conservative estimating, or professional judgment, and doses may be determined by the specific intrusion model. As discussed in Section 3.3 for intrusion scenarios, the current NRC guidance assumes complete mixing of any excavated material following the future intrusion event due to excavation and redistribution of soils near the point of excavation (see NUREG-1757, Volume 2, Revision 2, Appendix J, for examples).

4.5.2 Small Elevated Volumes and the Water-Dependent Pathway

The concept of a highly contaminated small subsurface volume and its impact on the water-dependent pathway is not easily defined. The size of a hypothetical “hot spot” volume applicable to all licensees is also not identified. More than just total activity, there are questions about partitioning between the solid and liquid phases, leachability, and transport time versus decay time. This analysis is site specific, but characterization methods remain unclear as an instrument scan is not available to determine how big such a hot spot might be and the impact on dose per radionuclide. Further, can spatial analysis and decision software estimate the minimum size of a volume for this purpose? Could this analysis become an issue of total radioactive inventory in the hot spot or just the activity concentration? A data gap exists for defining a subsurface soil hot spot, and specific guidance for licensees is needed.

5 STAGES OF THE SUBSURFACE DECISION FRAMEWORK

This section discusses methods and considerations for performing various types of subsurface radiological surveys ranging from HSAs through scoping, characterization, remedial action, confirmatory, and final status surveys. It also discusses how sampling and analysis can be optimized for some types of surveys using approaches such as “composite sampling” or surrogate ratios.

KEY POINTS

- The Performance-Based Subsurface Compliance Framework is presented.
- The role played by AOCs, CCMs, and DCGLs in the iterative DQO process is presented.
- SADA provides support for the MARSSIM RSSI process for subsurface soils.

Similar to the MARSSIM framework, Figure 5-1 shows the general flow of the subsurface decision framework. The different phases depict how the subsurface analysis moves from a very qualitative beginning to a more quantitative conclusion through a series of phases identified in the MARSSIM guidance. Each oval represents a major phase in the investigation. These phases are broadly defined to permit the flexibility needed to deal with various situations. Each arrow shows a potential path through the framework and is annotated by the output content from the previous phase. In turn, this output becomes the input for the next phase. The major theme is to use the HSA to create an initial CCM. Then, the output of each major phase (which serves as input for the next phase) includes the latest CCM update, as well as other relevant products. The end result is success in the compliance phase or a return to an interim phase under compliance failure. The framework suggests some methods that may be useful in compliance phase activities (NRC 2012, p. 13).

Figure 5-1 illustrates that phases are not necessarily unique and that data collected in one phase is important to others in the MARSSIM RSSI process.

There is no requirement that a unique final status survey (FSS) be performed only during the compliance phase, which is at the end of the decommissioning process. Data from other surveys conducted during the RSSI process—such as scoping, characterization, and remedial action support surveys—can provide valuable information for an FSS, provided the data are of sufficient quality (NRC 2006). It is important that survey and sample analysis methodologies be of sufficient quality throughout all phases to detect a low percentage of the $DCGL_V$. Ultimately, measurement data (bias, random, and gridded) from subsurface soils sampling will be combined and then illustrated in a 3D mapping through a kriging process. HSA survey data may be useful in an FSS if the data are of sufficient quality; this could be very important for early kriging and decision-making.

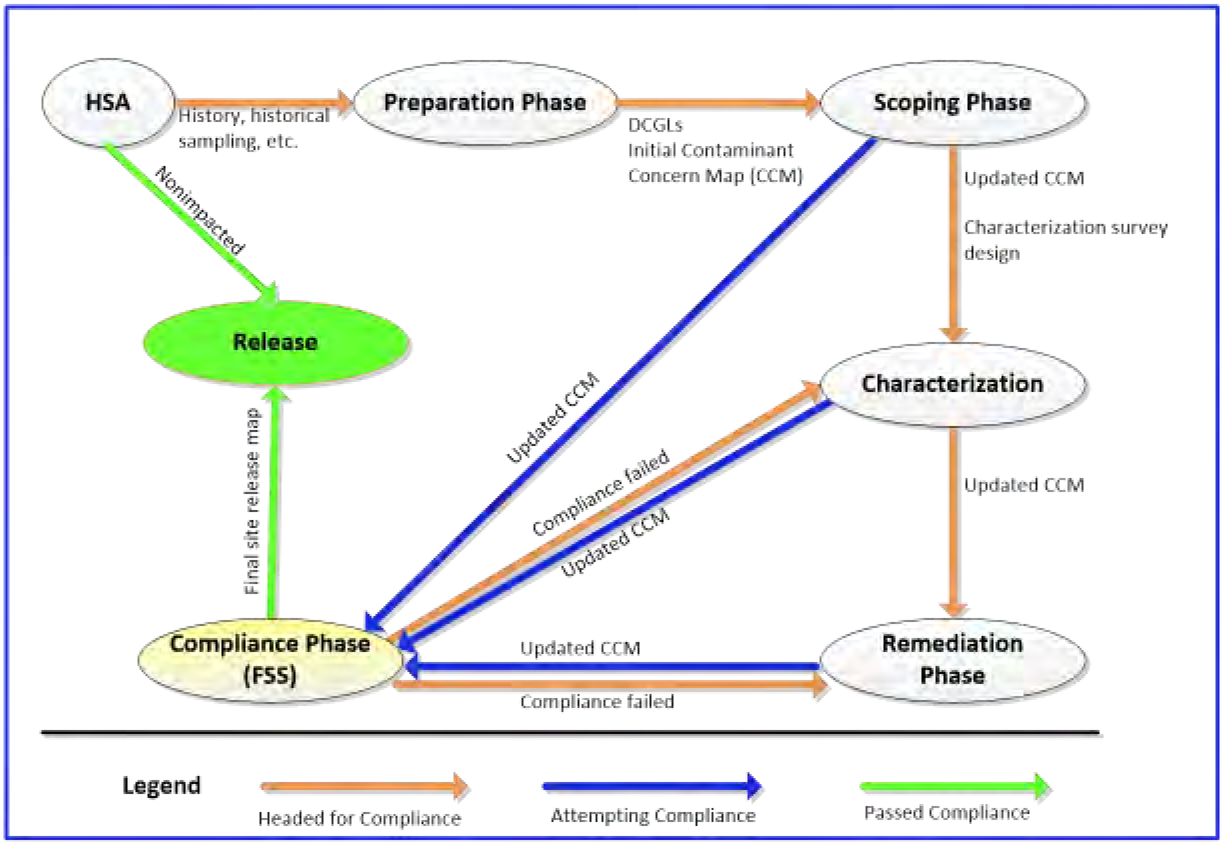

Figure 5-1 Flow Diagram for the Performance-Based Subsurface Compliance Framework

Source: Updated from NRC 2012, p. 13

Licensees may plan the different phases of the RSSI such that the data obtained will be of sufficient quality to serve or to supplement the compliance phase. The data quality objective (DQO) process may be applied to all phases of the RSSI, with DQOs developed that will be as robust as those typically developed for the FSS. This approach may result in more costly characterization or remedial action support surveys (to support the more stringent DQOs), which may be balanced against the elimination of a separate FSS (NRC 2006). Appendix D to MARSSIM discusses the DQO process in detail (NRC 2000a).

MARSSIM's RSSI process has six principal steps that apply to the framework for subsurface compliance. These principal steps have the following important properties, summarized as follows (NRC 2000a):

- An HSA is conducted. This determines the likelihood of contamination in a very qualitative way.
- If warranted, a scoping survey is performed to assess the severity and magnitude of the contamination and possible remedial action.
- If warranted, a characterization effort is conducted to better delineate the extent of contamination.

- If warranted, a remediation effort can be conducted to remove or mitigate activity levels below each DCGL.

- An FSS is conducted.

- The assessment is conducted, and the site passes or fails.

NUREG/CR-7021 provides a geospatial modeling decision framework for conducting a subsurface vadose zone compliance survey and analysis. This framework proposes a method to extend the MARSSIM guidance into the vadose zone, with possible applications to ground water as well (Stewart 2012).

Figure 5-2 illustrates the RSSI process with emphasis on AOC, CCM, and DCGL development.

As contamination moves, it disperses (i.e., the concentration decreases as it moves farther away from the source of pollution). Because of the dispersion, there are different concentrations of contaminants at different points in the subsurface and aquifer. Surveys focus on the width, depth and shape of the plume. All collected data are illustrated with a 3D CCM.

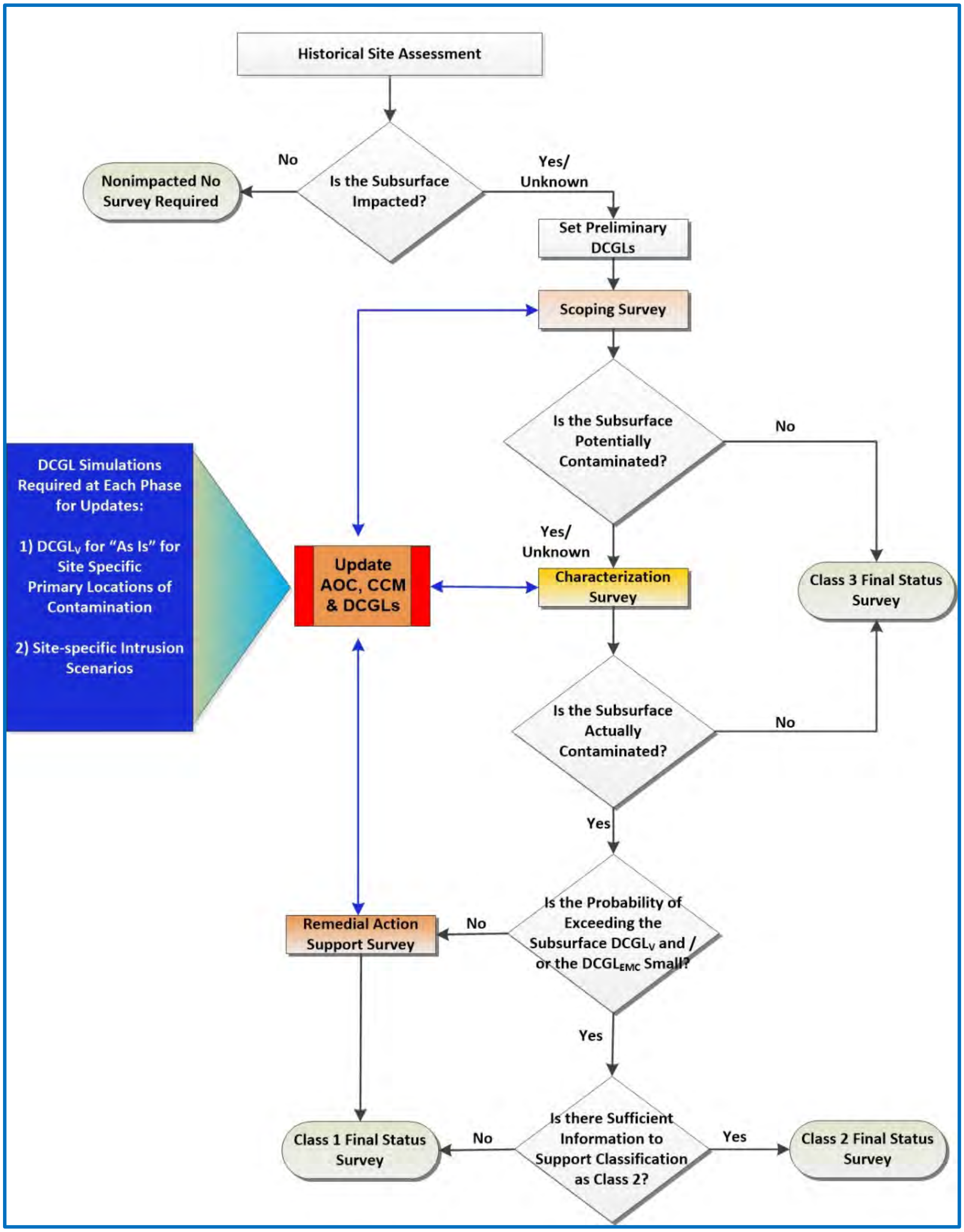

Figure 5-2 The RSSI in Terms of Area Classification and DCGL Iteration

Source: Updated from NRC 2000a, p. 2-17

5.1 DATA LIFE CYCLE AND DATA QUALITY OBJECTIVES

The NRC recommends using the DQO process to establish criteria for data quality and develop survey designs. The process uses a graded approach to data quality requirements, based on the type of survey being designed and the risk of making a decision error based on the data collected. This process aligns the resources expended to collect and analyze data with the risk significance of the data (NRC 2006).

MARSSIM explains the Data Life Cycle in detail; however, the information is repeated here and directed specifically to subsurface material surveys.

The planning phase of the Data Life Cycle is carried out using the DQO process. This process is a series of planning steps based on the scientific method for establishing criteria for data quality and developing survey designs (EPA 1994, 1987a, 1987b). The level of effort associated with planning depends on the complexity of the survey. Large, complicated sites generally require a significant effort during the planning phase, while smaller sites may not require as much planning effort (NRC 2000a).

The guidance document leads the user through the three phases of the sampling and analysis process shown in Figure 5-3: planning, implementation, and assessment. Planning involves “asking the right questions.” Using a systematic planning process such as the DQO process helps in this regard. DQOs are the specifications needed to develop a plan for the project such as a quality assurance project plan (QAPP) or a waste analysis plan. Implementation involves using the field sampling procedures and analytical methods specified in the plan and taking measures to control errors that might be introduced along the way. Assessment is the final stage in which the results of the study are evaluated in terms of the original objectives and decisions are made on the management or treatment of the waste (EPA 2002b).

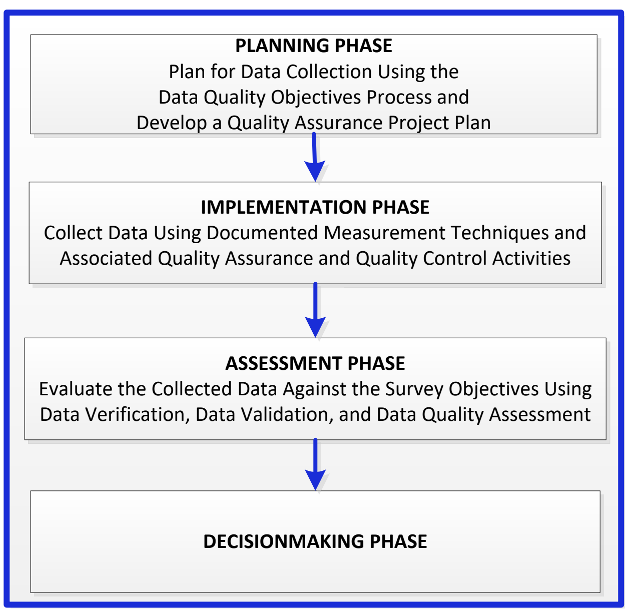

Figure 5-3 QA Planning and the Data Life Cycle

Source: NRC 2000a

DQOs are developed on a site-specific basis. However, because of the large variation in the types of radiation sites, it is impossible to provide criteria that apply to every situation. MARSSIM (NRC 2000a) describes generally acceptable approaches for the following:

- planning and designing scoping, characterization, remediation support, and FSSs for sites with surface soil and building surface contamination
- HSA
- QA/quality control (QC) in data acquisition and analysis
- field and laboratory methods and instrumentation and interfacing with radiation laboratories
- statistical hypothesis testing and the interpretation of statistical data documentation

Thus, MARSSIM provides standardized and consistent approaches for planning, conducting, evaluating, and documenting environmental radiological surveys, with a specific focus on the FSSs that are carried out to demonstrate compliance with cleanup regulations. These approaches may not meet the DQOs at every site, so other methods may be used to meet site-specific DQOs, as long as an equivalent level of performance can be demonstrated.

Planning radiological surveys using the DQO process can improve the survey effectiveness and efficiency and thereby the defensibility of decisions. It also can minimize expenditures related to data collection by eliminating unnecessary, duplicative, or overly precise data. The use of the DQO process ensures that the type, quantity, and quality of environmental data used in decision-making will be appropriate for the intended application. It provides systematic procedures for defining the criteria that the survey design should satisfy, including when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform (NRC 2000a).

The expected output of planning a survey using the DQO process is a QAPP. The QAPP integrates all technical and quality aspects of the Data Life Cycle and defines in detail how specific QA and QC activities will be implemented during the survey (NRC 2000a).

The DQO process provides for early involvement of the decisionmaker 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 (NRC 2000a):

- 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 which 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 5-4. 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. 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 since 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 (MARSSIM, Appendix D (NRC 2000a)). As indicated, these steps are well defined and further explained in MARSSIM and NUREG-1757.

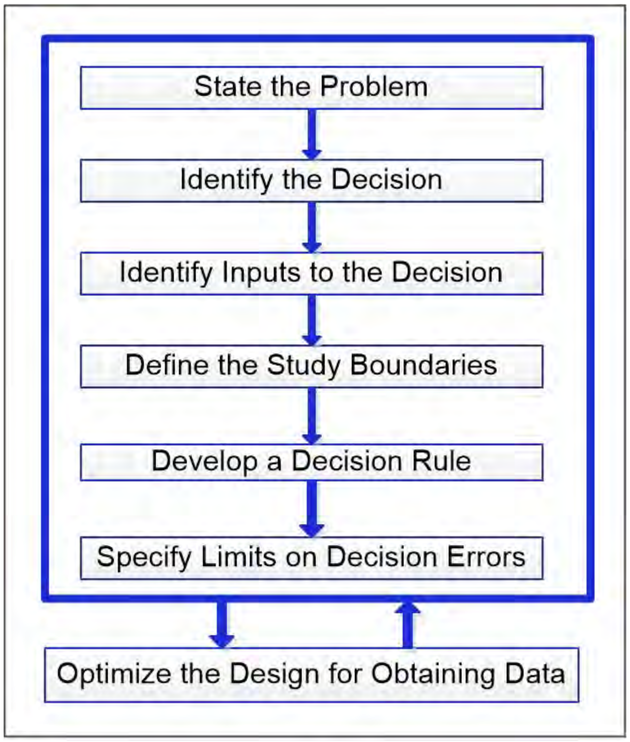

Figure 5-4 The Seven Steps of the DQO Process

Source: NRC 2000a, EPA 2002b

5.2 HISTORICAL SITE ASSESSMENT

The licensee should first determine whether there is a need for surveys of subsurface residual radioactivity. Performance of an HSA will usually be sufficient to indicate whether there is likely to be subsurface residual radioactivity. If the HSA indicates that there is no likelihood of substantial subsurface residual radioactivity, subsurface surveys are not necessary. If the HSA indicates that there is substantial[15] subsurface residual radioactivity and the licensee plans to terminate the license with some subsurface residual radioactivity in place, an FSS is required. To demonstrate compliance with the radiological criteria for license termination, the FSS must

15 NUREG-1757, Volume 2, Revision 2, does not define "substantial."

consider the subsurface residual radioactivity. Scoping and characterization surveys determine the depth of the residual radioactivity for the FSS (NRC 2020b), and all licensees must keep records of subsurface contamination for decommissioning as required in 10 CFR 20.1501.

Residual radioactivity can come from use of source, byproduct, and special nuclear materials, as well as naturally occurring radioactive material (NORM), naturally occurring and accelerator-produced radioactive material (NARM), and technologically enhanced naturally occurring radioactive material (TENORM). This material may be related to commercial, research, education, or defense uses. The material might be—

- used or stored at sites and facilities licensed to handle radioactivity
- a commercial product purposely containing radionuclides (e.g., smoke detectors)
- a commercial product incidentally containing radionuclides (e.g., phosphate fertilizers)
- associated with NORM and TENORM (NRC 2009a)

Investigators should collect all relevant information on the potential study area, if it has not already been gathered for a larger HSA for the entire site. As information is sought and retrieved, the investigators should be mindful of constructing the initial CCM and, potentially, the full CSM. Any inquiries that may contribute to the CCM are particularly useful to this framework. Background information on geological properties, ground water flow, and historical samples and their locations is useful in creating a CCM that is as informed as possible in the preparation phase. It is anticipated that a GIS or similar spatial analysis tool will be involved in the creation and maintenance of the CCM. For this reason, the coordinate system (and possibly the projection) of any spatially referenced information should be noted. This includes not only sample locations but other GIS content such as road layers, building layers, topography, property boundaries, and so forth. Once a historical query has been exhausted, the investigation moves to the scoping phase.

The following are the primary objectives of the HSA (NRC 2000a):

- Identify potential sources of contamination.
- Determine whether sites pose a threat to human health and the environment.
- Differentiate impacted from nonimpacted areas.
- Provide input to scoping and characterization survey designs.
- Assess the likelihood of contaminant migration.
- Identify additional potential radiation sites related to the site being investigated.

ANSI/ANS Standard 2.17 indicates that facilities are to be characterized in terms of their specific components, procedures, and processes for which an abnormal radionuclide release may occur, with the goal being to identify the potential release modes along with the likelihood of these releases (ANS 2010). As part of the HSA, specific facility information that may be of interest includes the locations and characteristics (e.g., dimensions, construction materials, hydraulic properties, radionuclide inventories) of the following relevant entities (ANS 2010):

- surface facilities (e.g., spent fuel pools, holding ponds, condensate tanks, pipelines)

- liquid waste management systems (tanks should be explicitly identified in the list of facilities)

- subsurface facilities (e.g., spent fuel pools, drains, pipes, conduits, artificial fill, backfill, pads, foundations, and the associated vadose zone)

- engineered barriers (e.g., liners, caps, cutoff walls, leak detection systems, and interceptor wells)

- well construction data (e.g., grouted and screened intervals, screen and casing type, depth, diameter, perforation, surface seals, aquifers penetrated, location, elevation, use, owner, discharge rates, static hydraulic heads, and drawdown)

- abandoned wells and piezometers, along with the method of abandonment

For NPPs and RTRs, most of the records listed below could be grouped as the 10 CFR 50.75(g) file, but the following specific types of documents are expected to be reviewed:

- license and technical specifications
  - technical specification changes
  - license amendments

- original plant design
  - function and purpose of systems and structures
  - plant operating parameters
  - plant operating procedures

- original plant construction drawings and photographs
  - specifications for systems and structures
  - field changes/as built drawings
  - site conditions

- plant operating history
  - abnormal operating reports (including the Groundwater Protection Initiative and annual radiological environmental operating report
  - licensee event reports
  - plant information reports
  - radiological occurrence reports
  - radiological incident reports
  - condition reports
  - plant operating procedures regarding spills and unplanned releases
  - plant operations logbooks
  - Radiological Environmental Monitoring Program and radiological environmental technical specification reports
  - monthly plant operations reports
  - semiannual plant operations reports

- work control documents and site modifications
  - job orders
  - plant alterations
  - engineering design change requests
  - plant modifications
  - maintenance requests

- radiological surveys and assessments
  - radiological surveys performed in support of normal plant operations and maintenance
  - radiological surveys performed in support of special plant operations and maintenance
  - radiological assessments performed in response to radioactive spills or events
  - scoping and characterization surveys performed as part of decommissioning plan (DP) development

MARSSIM contains a complete description of the HSA. Figure 5-5, which has been updated to accommodate DCGL and CCM requirements, presents the HSA portion of the RSSI process. Figure 5-6 presents an example report format.

The initial design of the CSM, described in Section 5.3.1, is based on existing site data compiled during previous studies. These data may include site sampling data, historical records, aerial photographs, maps, and any soil surveys, as well as information on local and regional conditions relevant to radionuclide migration and potential receptors. Published information on local and regional climate, soils, hydrogeology, and ecology may be useful. In addition, information on the population and land use at and surrounding the site will be important to identify potential exposure pathways and receptors. MARSSIM Section 3.4 discusses the collection of existing data specific to sites contaminated with radioactive materials (NRC 2000a).

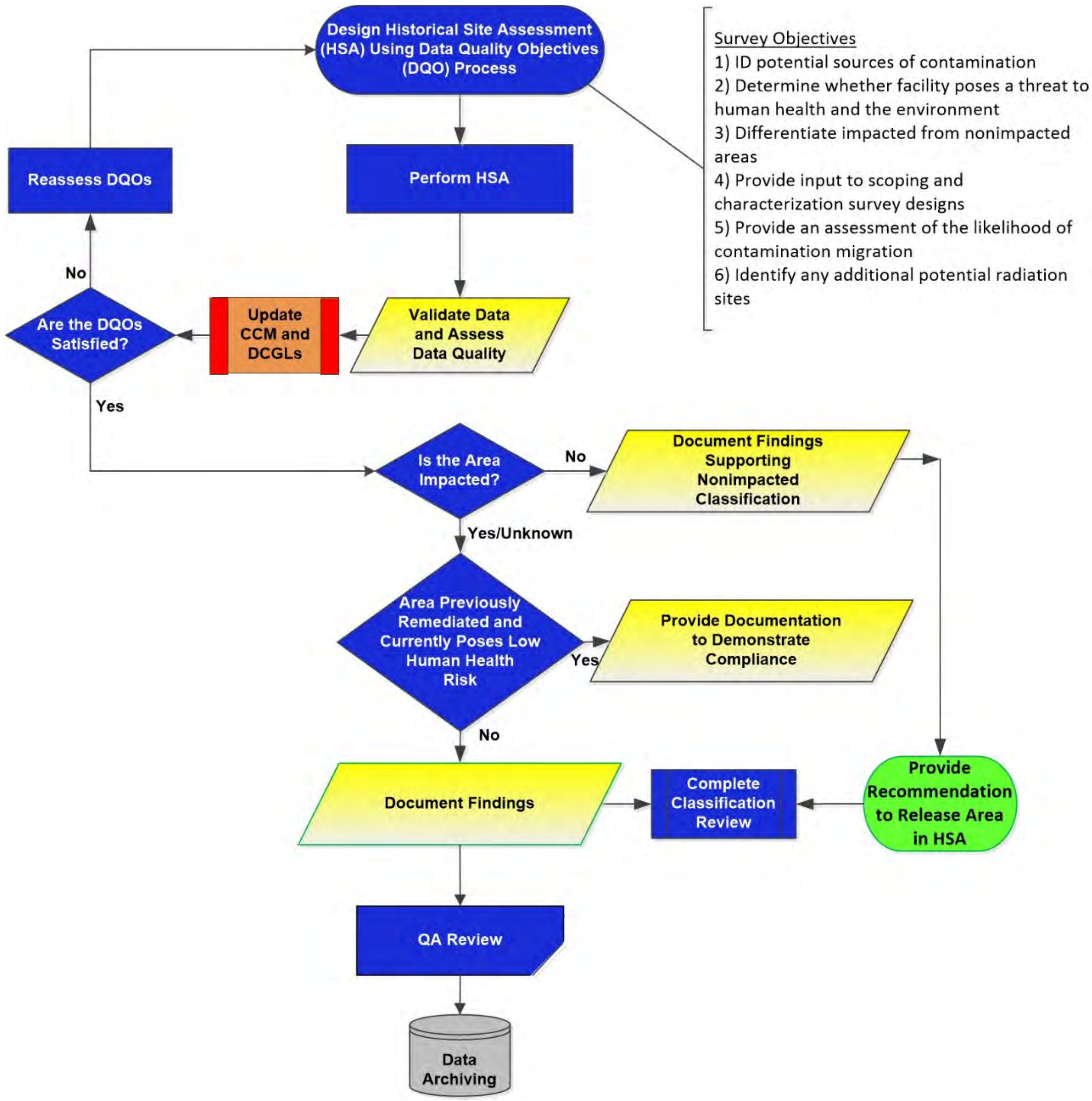

Figure 5-5 The HSA Portion of the RSSI Process

Source: Updated from NRC 2000a

1. Glossary of Terms, Acronyms, and Abbreviations
2. Executive Summary
3. Purpose of the Historical Site Assessment
4. Property Identification
    - 4.1 Physical Characteristics
        - 4.1.1 Name—owner/operator name, address, license number, and docket
        - 4.1.2 Location—street address, city, county, state, geographic coordinates
        - 4.1.3 Topography—USGS 7.5-minute quadrangle or equivalent
        - 4.1.4 Stratigraphy
    - 4.2 Environmental Setting
        - 4.2.1 Geology
        - 4.2.2 Hydrogeology
        - 4.2.3 Hydrology
        - 4.2.4 Meteorology
5. Historical Site Assessment Methodology
    - 5.1 Approach and Rationale
    - 5.2 Boundaries of Site
    - 5.3 Documents Reviewed
    - 5.4 Property Inspections
    - 5.5 Personal Interviews
6. History and Current Usage
    - 6.1 History—years of operation, type of facility, description of operations, regulatory involvement, permits and licenses, waste handling procedures
    - 6.2 Current Usage—type of facility, description of operations, probable source types and sizes, description of spills or releases, waste manifests, radionuclide inventories, emergency or removal actions
    - 6.3 Adjacent Land Usage—sensitive areas such as wetlands or preschools
7. Findings
    - 7.1 Potential Contaminants
    - 7.2 Potential Contaminated Zones (Areas/Volumes)
        - 7.2.1 Impacted Zones—known and potential
        - 7.2.2 Nonimpacted Zones
    - 7.3 Potential Contaminated Media
    - 7.4 Related Environmental Concerns
8. Conclusions
9. References
10. Appendices
    - A. Conceptual Model and Site Diagram Showing Classifications
    - B. List of Documents
    - C. Photo Documentation Log
      Original photographs of the site and pertinent site features

Figure 5-6 Example HSA Report Format

Source: Updated from NRC 2000a

5.3 SCOPING SURVEY

If the data collected during the HSA indicate an area is impacted, a scoping survey could be performed. Scoping surveys provide site-specific information based on limited measurements.

The following are the primary objectives of a scoping survey:

- Perform a preliminary hazard assessment.
- Evaluate whether the survey plan can be optimized for use in the characterization or FSSs.
- Provide data to complete the site prioritization scoring process (Comprehensive Environmental Response, Compensation, and Liability Act and Resource Conservation and Recovery Act (RCRA)[16] sites only).
- Provide input to the characterization survey design if necessary (NRC 2000a).
- Evaluation of background reference levels if contaminant is part of NORM.
- Support classification of all or part of the site as impacted (contaminated zones) or nonimpacted and perhaps define areas requiring remediation.

Scoping surveys are conducted after the HSA is complete and consist of judgmental measurements based on the HSA data. Sufficient information should be collected to identify situations that require immediate radiological attention (NRC 2000a). Specifically, the scoping survey performed with coring technology should identify the depth of the contaminated layer zone, the thickness of the contamination, verification of contaminants, and a reasonable estimate of the areal extent (boundaries) of contamination. Contamination of the aquifer should be confirmed.

For scoping survey activities that provide an initial assessment of the radiological hazards at the site, or provide input for additional characterization, the survey data are used to identify the locations and general extent of residual radioactivity. Scoping survey data that are expected to be used as FSS data should be of the same quality as that expected from an FSS (NRC 2000a).

MARSSIM gives a complete description of the scoping survey. Scoping surveys may be designed to meet the objectives of the FSS such that the scoping survey report is also the FSSR (NRC 2000a). Figure 5-7 presents the scoping survey portion of the RSSI process with updates to accommodate DCGL and CCM requirements.

Following Figure 5-7 are suggestions for achieving some of the listed objectives.

[16] RCRA gives the EPA authority to control hazardous waste from “cradle to grave.”

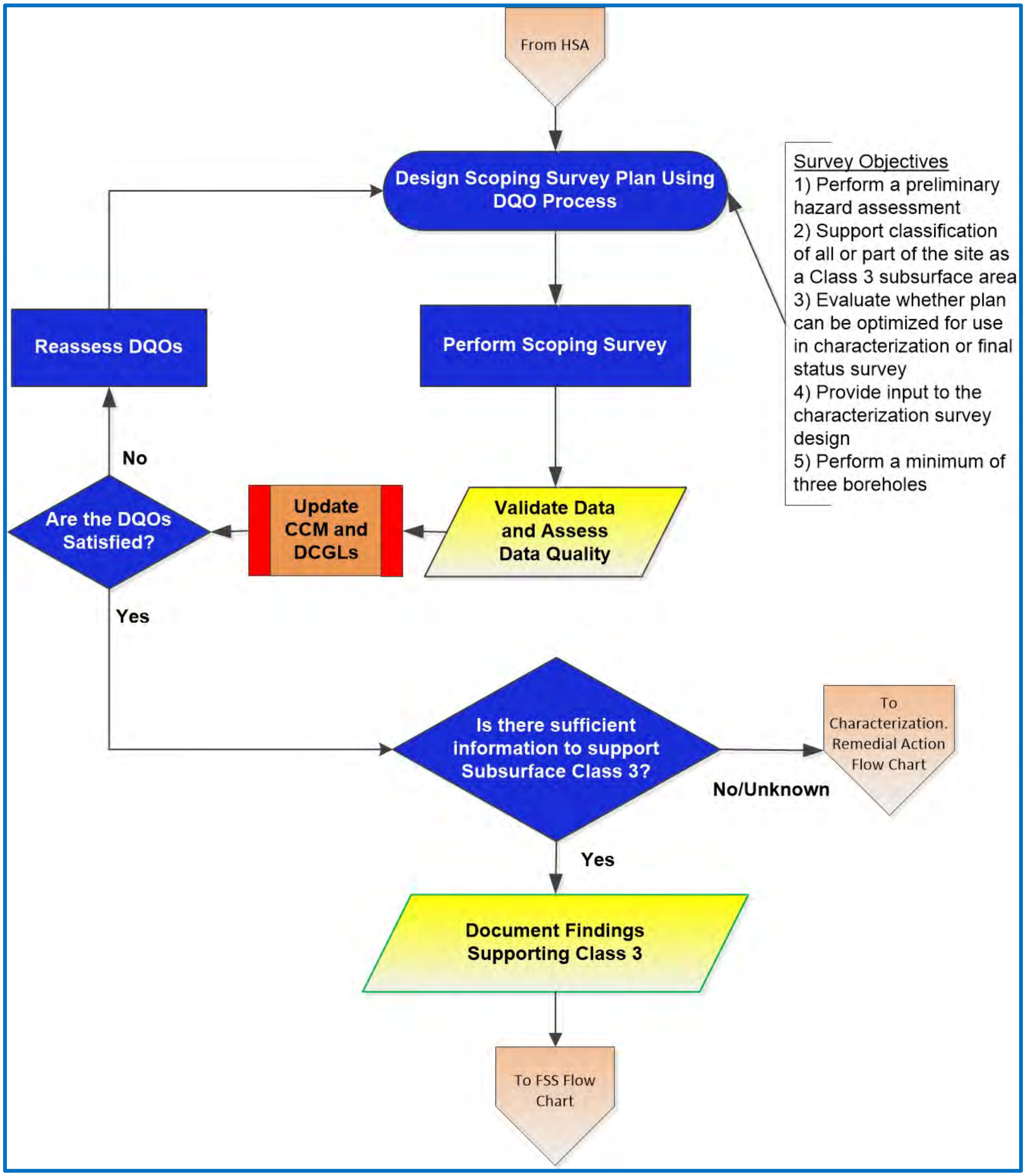

Figure 5-7 The Scoping Survey Portion of the RSSI Process

Source: Updated from NRC 2000a

5.3.1 Develop a Preliminary Conceptual Site Model

Using all the information gathered in the HSA, a continuous map of the likelihood that contamination exists in the study area should be created. Specifically, the map should delineate for the entire area the currently known likelihood that the $DCGL_V$ would be exceeded. The preliminary CSM should be used to inform the scoping phase of the project. The CSM can be created in true 3D or in 2D if no useful variation by depth is available. For a 3D creation, each layer in the subsurface would need to be delineated relative to the decision criteria. This is a preferable scenario but may not be feasible at this time. If not feasible, then a 2D map shows where contamination may exist *at some depth* in the subsurface (Stewart 2012). Figure 5-8 illustrates an example cross-sectional view, and Figure 5-9 presents a simple 2D CSM for a burial pit to begin the iterative process. Figure 5-10 shows an example CSM diagram for contaminated soil. Perhaps all three types of figures should be developed for sites undergoing decommissioning to begin to satisfy stakeholders concerned about the legitimacy of the site study and decommissioning team efforts. Figures 5-8, 5-9, and 5-10 show examples of the three types of figures.

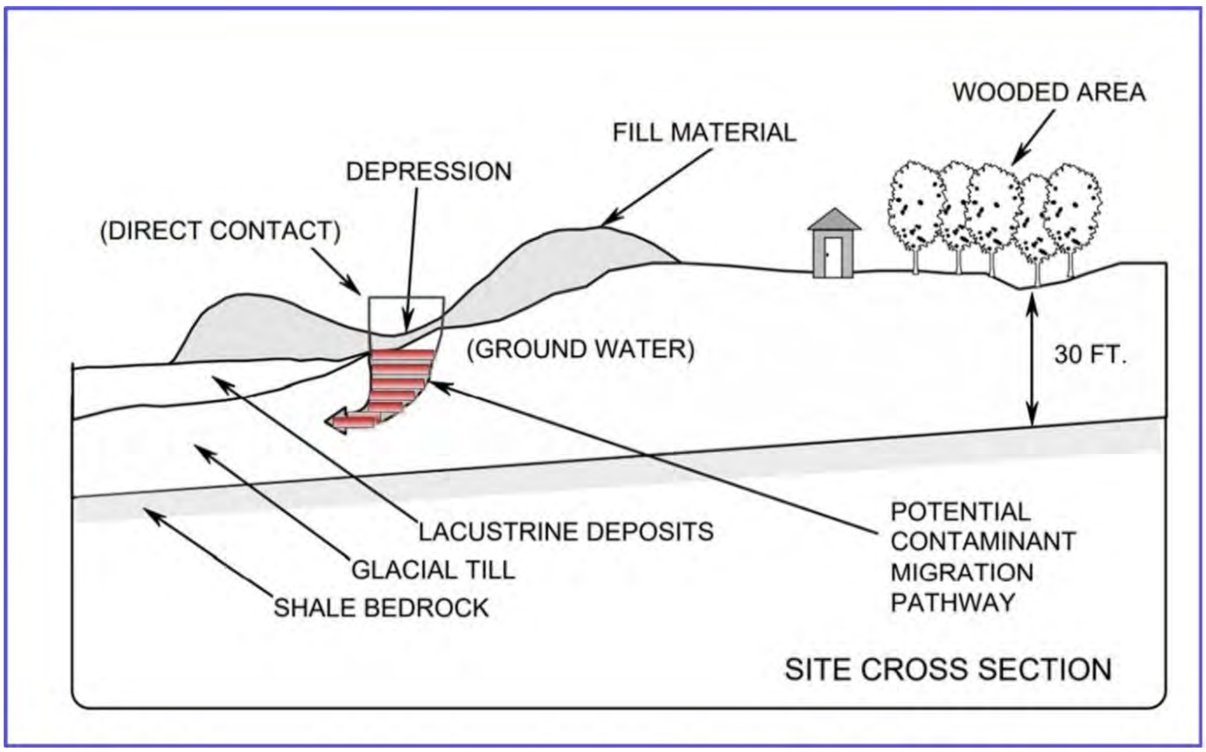

Figure 5-8 An Example Cross Section

Source: EPA 2000

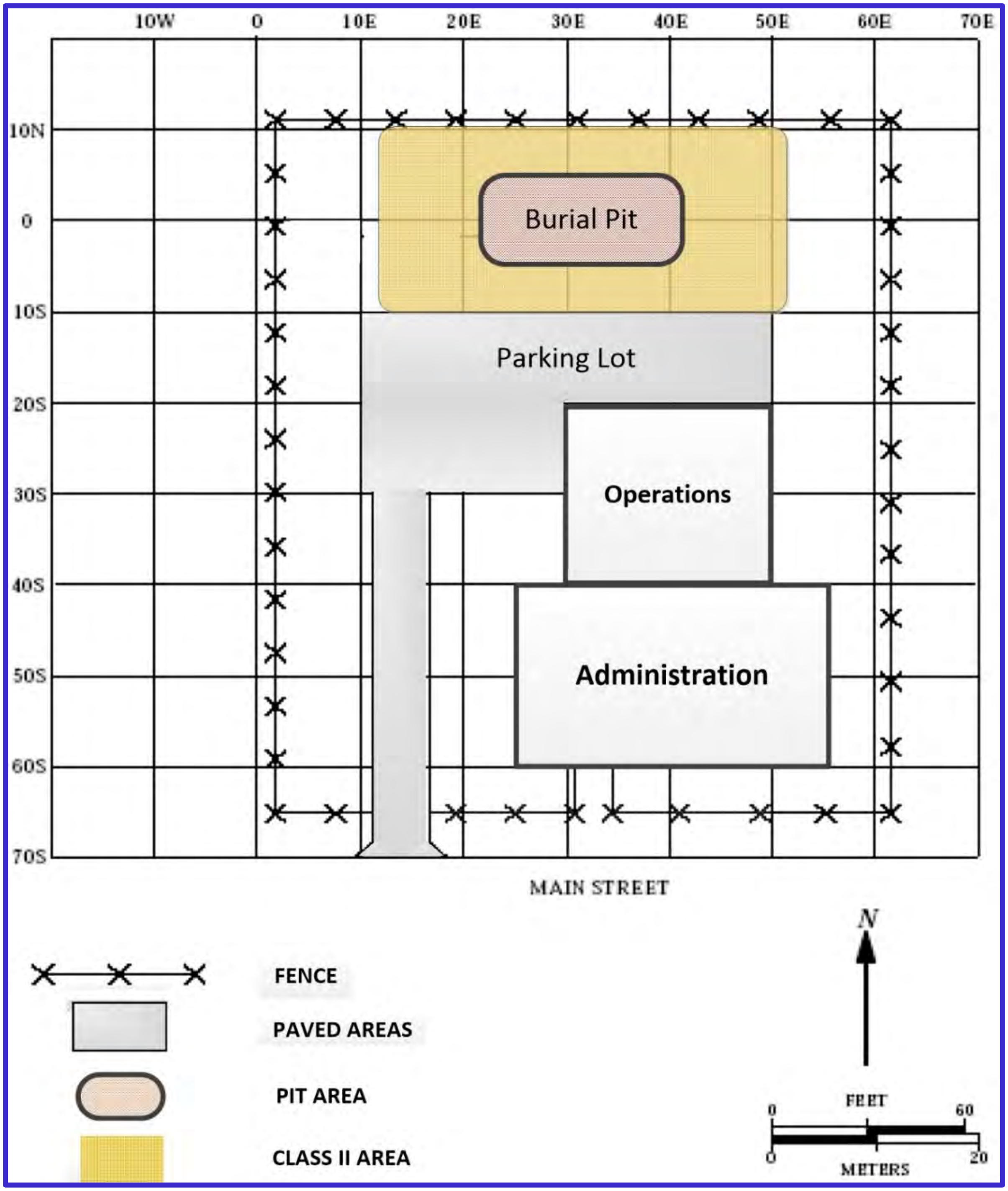

Figure 5-9 A Simple 2D Example of CSM for Burial Pit

Source: Updated from NRC 2000a, Figure A.1

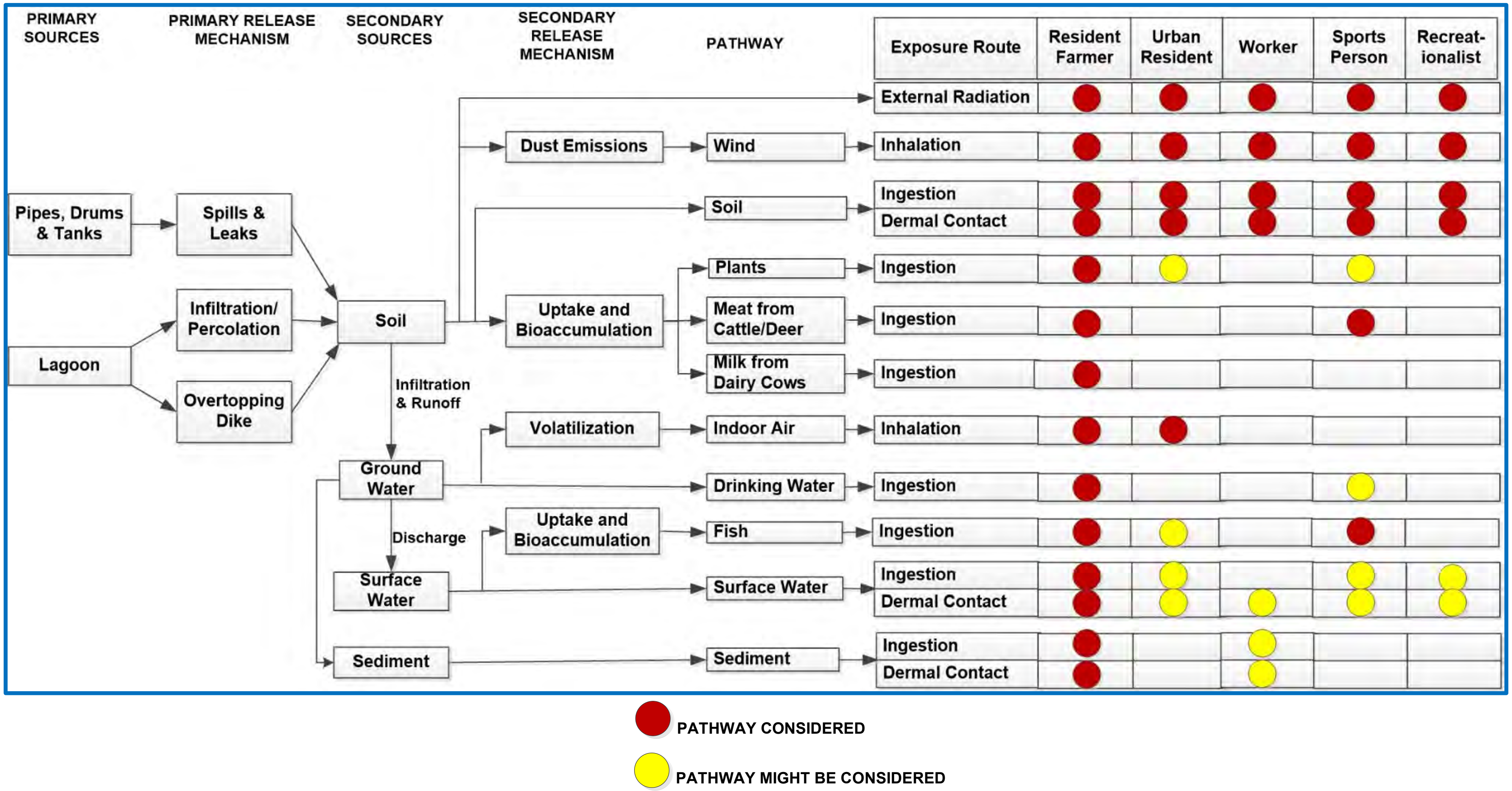

Figure 5-10 Example CSM Diagram for Contaminated Soil

Source: EPA 1989, NRC 2020e

5.3.2 Develop Sampling and Analysis Plan for Subsurface Soils

Except for an intrusion scenario, exposure to subsurface contamination may occur when radionuclides migrate down to an underlying aquifer. Perhaps subsurface sampling should also focus on collecting the data required for modeling the migration to ground water pathway (EPA 2000). Measurements of soil characteristics and estimates of the area and depth of contamination and the average contaminant concentration in each source area are needed to supply the data necessary to calculate the migration to ground water in software simulations by RESRAD or DandD.

Source areas are the decision units for subsurface soils. A source area is defined by the horizontal extent and vertical extent or depth of contamination, recognizing that original sources could have been transported over time following original placement. Sites with multiple sources should develop separate DCGLs for each source. (Note that this is not a discussion of MARSSIM surface survey units.)

The sampling and analysis plan (SAP) developed for subsurface soils should specify sampling and analytical procedures, as well as the QA and QC procedures. To identify the appropriate procedures, the onsite DCGLs must be estimated with the consideration that an offsite critical group might be the dominant receptor.

The primary goal of the subsurface sampling strategy is to estimate the mean radionuclide concentration and average soil characteristics within the source area. As with the surface soil sampling strategy, the subsurface soil sampling strategy follows the DQO process. Figure 5-11 summarizes SAP design considerations for subsurface soils (EPA 2000).

If the radionuclide of concern (ROC) is not present in background, the decision rule is based on comparing the mean radionuclide concentration within each contaminant source with a source-specific DCGL.

Current investigative techniques and statistical methods cannot accurately determine the mean concentration of subsurface soils within a contaminated source without a costly and intensive sampling program that is well beyond the level of effort generally appropriate for screening. Thus, conservative assumptions should be used to develop hypotheses on likely contaminant distributions (EPA 2000). The choice of survey technique should be commensurate with the intended use of the data, including possible future utilization of the results to supplement the FSS data (NRC 2006).

This guidance bases the decision to investigate a source area further on the highest mean soil boring contaminant concentration within the source, reflecting the conservative assumption that the highest mean concentration among a set of borings taken from the source area represents the mean of the entire source area. Similarly, estimates of contaminant depths should be conservative. The investigation should include the maximum depth of contamination encountered within the source. Guidance is needed on whether to sample below the water table.

For each source, the guidance recommends taking three soil borings or more in the areas suspected of having the highest contaminant concentrations within the source area. An equivalent number should be taken in a background reference area if the contaminant is part of NORM. If coring can be performed to identify the edge of the contamination, those samples should be taken as well. These subsurface soil sampling locations are based primarily on knowledge of likely surface soil contamination patterns (see Figure 5-12) and subsurface conditions. However, buried radioactive material may not be discernible at the surface.

Information on past practices at the site included in the CSM can help identify subsurface source areas (EPA 2000).

Sampling should begin at the ground surface and continue until the water table is reached, if practical. Sampling through the water may be necessary if the source is upgradient of the water table and the contaminant is configured as shown in Figure 2-1(c) above. Subsurface sampling intervals can be adjusted at a site to accommodate site-specific information on subsurface contaminant distributions and geological conditions (e.g., very deep water table, very thick uncontaminated unsaturated zone, user well far beyond edge of site, soils underlain by karst or fractured rock aquifers). Sample splits and subsampling may be performed according to EPA/600/R-92/128, “Preparation of Soil Sampling Protocols: Sampling Techniques and Strategies,” issued July 1992 (Mason 1992).

Soil cores should be taken from the soil boring using either split-spoon sampling or other appropriate sampling methods. It is recommended that core samples also be obtained and monitored intact in the field to determine if layers of radioactivity are present. In addition, the use of a subsurface sampling technique, which results in a borehole or soil face, may be logged using a gamma scintillation detector. This enables scanning of the exposed soil surface to identify radioactive contamination within small fractions of hole depth, thus facilitating the identification of the presence and depth distribution of subsurface radioactivity. This information may be used to direct further core sampling and laboratory analysis as warranted.

Grid sampling is often used for these pilot studies, scoping studies, and exploratory studies using the assumption that there are no patterns or regularities in the distribution of the contaminant of interest (EPA 2002c).

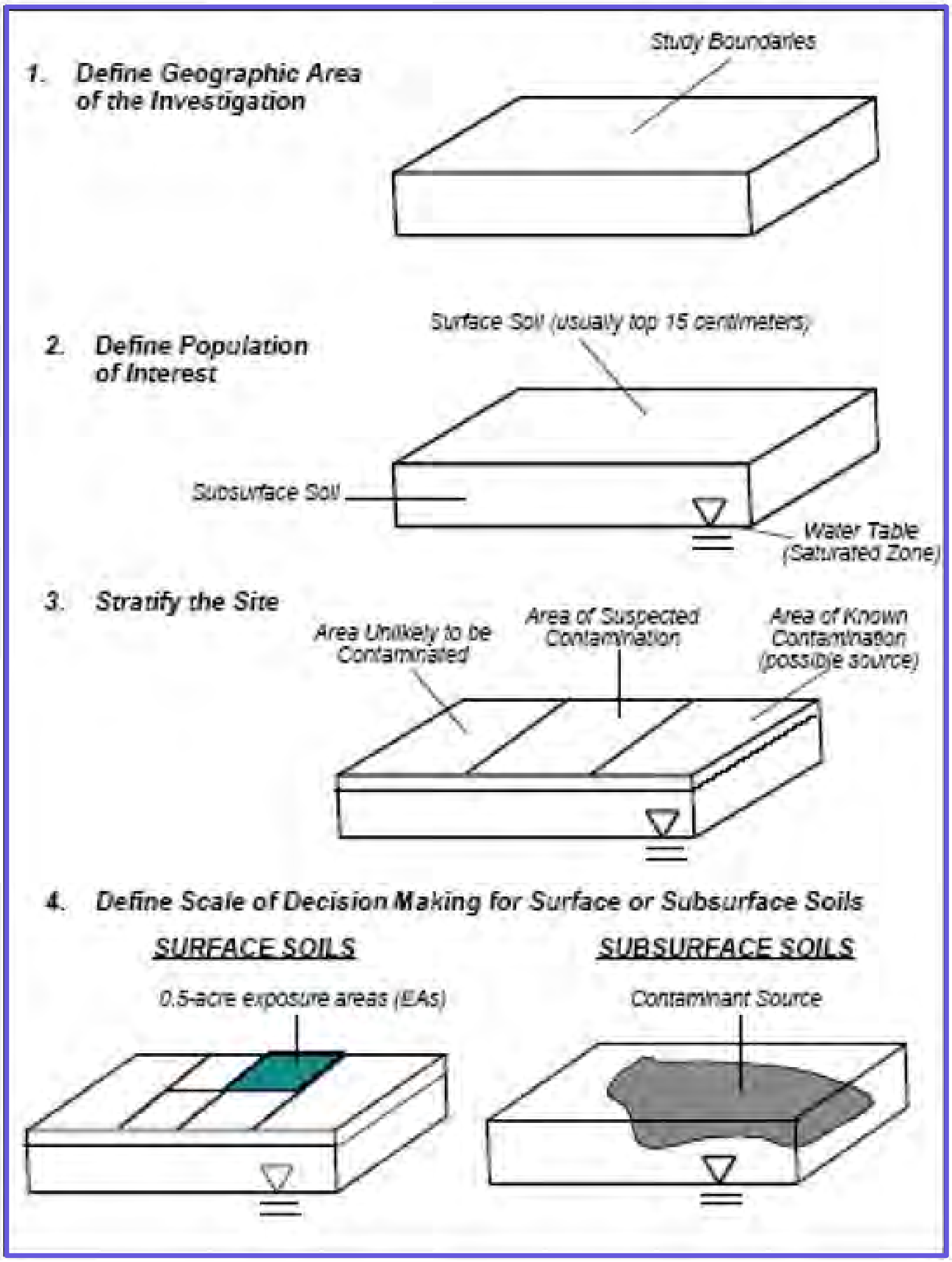

Figure 5-11 Define the Study Boundaries

Source: EPA 2000

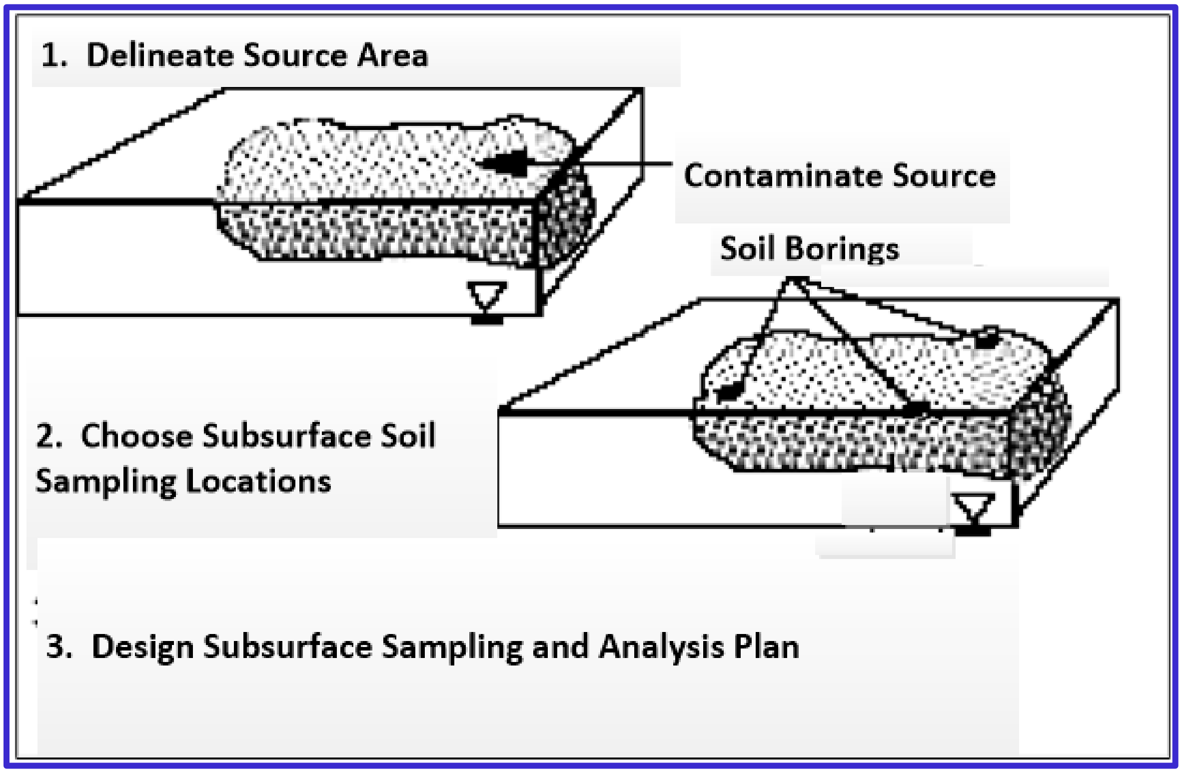

Figure 5-12 Designing a Scoping Plan for Subsurface Soils (Radionuclide Not Present in Background)

Source: EPA 2000

Survey data are converted to the same units as those in which DCGLs are expressed. Potential radionuclide contaminants at the site are identified using direct measurements or laboratory analysis of samples. The data are compared to the appropriate regulatory DCGLs. If there are no exceedances of the DCGLs, then investigators may consider attempting to move into the compliance phase. If there are exceedances, they should be addressed in the characterization phase, remediation phase, or in both phases. Either way, the CCM is updated with the results of the survey and passed to the next phase (NRC 2012).

Some other objectives of the scoping include identifying site contaminants, determining relative ratios of contaminants, and establishing DCGLs and conditions for the contaminants that satisfy the requirements of the responsible agency. Identification of potential radionuclide contaminants at the site is generally performed through laboratory analyses, such as alpha and gamma spectrometry. These analyses are used to determine the relative ratios of the identified contaminants, as well as isotopic ratios for common contaminants like uranium and thorium. This information is essential in establishing and applying the DCGL for the site (NRC 2000a). A future exposure scenario is assumed to be plausible (e.g., excavation), or a value protective for the ground water pathway can be estimated (NRC 2012). Figure 5-13 illustrates the potential results of a scoping survey resulting in 16 borings including a search for the extent of an elevated volume. The DQO process requires searching for the extent of any elevated areas, and planning includes gathering as much data as possible while the survey team is in the field. This early definition of a contaminated zone is possible through use of field measuring units with near real-time assessment such as the In Situ Object Counting System ™ (ISOCS), a sodium iodide (NaI) detector, or other field-deployed gamma spectrometer. Section 12 describes the search pattern for the elevated zone. Figure 5-14 illustrates the data presented in a 3D format.

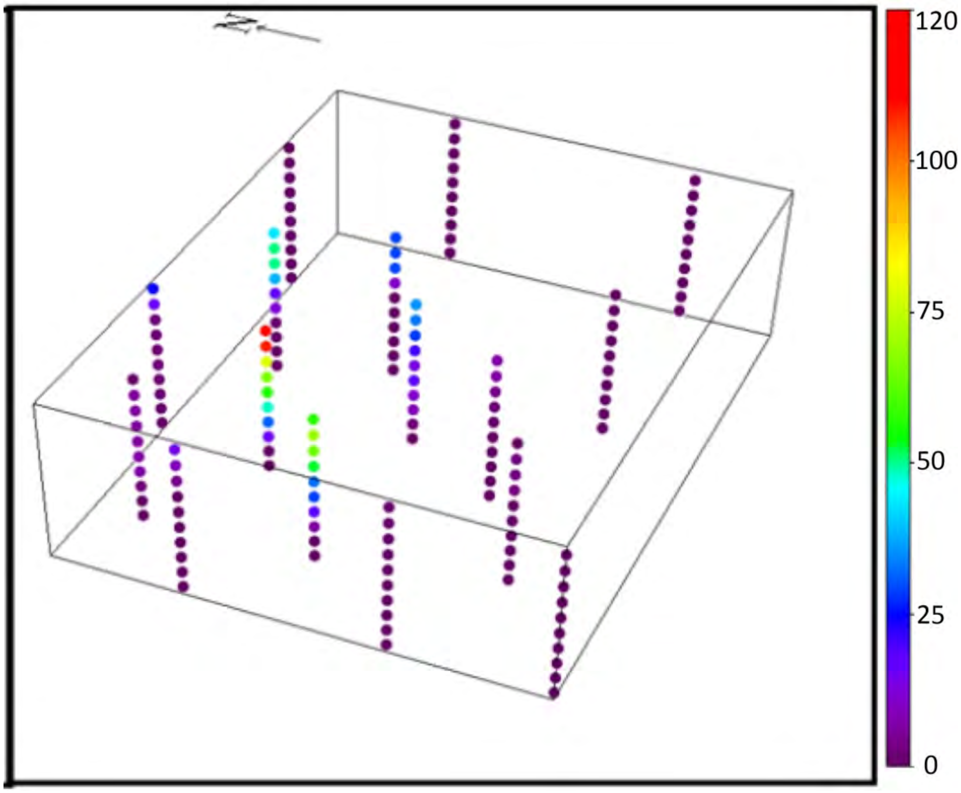

Figure 5-13 Results (pCi/g) of Core Sampling and In-Field Measurement Techniques

Source: NRC 2012

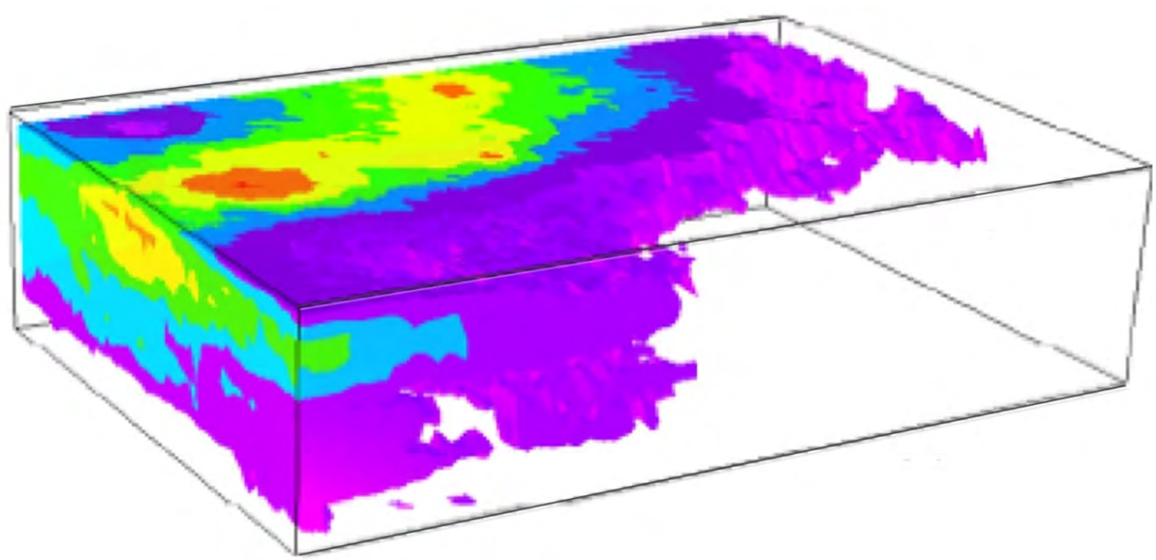

Figure 5-14 3D Rendition of Core Sampling and In-Field Measurement

Source: NRC 2012

Section 12 discusses in detail how to survey elevated zones (hot spots); there are three potential choices, or a combination of the three may be used:

(1) Perform a star pattern search, and 3D-map the results. This is called “second-phase sampling” and should be used when a hot spot is suspected during a scoping or characterization survey.

(2) Develop and perform a 3D search using 2D software such as Visual Sample Plan (VSP) (Matzke et al. 2014).

(3) Implement a sophisticated SADA “hot spot” strategy with 3D mapping software as described in NUREG/CR-7021 (NRC 2012, p. 492).

5.3.3 Decide on Compliance or Characterization

One of the goals of subsurface investigations is to identify the contaminated volumes that present a dose above the release criteria and, following remediation, gather a reasonable proof that the site is acceptable for either restricted or unrestricted release. The analysis will use both biased and random sample results. There may be usable results if the HSA and the scoping survey together have at least three cores of data to support the configuration presented in Figure 2-1 that best represents the site. Results of site-specific RESRAD simulations should be available to establish the “as is” $DCGL_V$, the $DCGL_W$, and EMCs, developed in Section 8, for applicable intrusion scenarios (e.g., the basement excavation and well drilling scenarios).

For restricted release, the release considerations are similar but with consideration of exposure scenarios for the case that institutional controls are in effect, as well as for cases when institutional controls are no longer in effect. For the case when institutional controls are no longer in effect, a higher allowable limit (times 4 or 20) or 100 or 500 mrem/year would apply.

If results are a small fraction[17] of any applicable DCGL, the site subsurface is a Class 3, and a Class 3 survey may be performed; an FSSR would be submitted. Otherwise, the licensee should move to the characterization phase.

5.4 CHARACTERIZATION PHASE

This section is generally adopted from guidance in MARSSIM (NRC 2000a), NUREG/CR-7021 (NRC 2012), and NUREG-1757, Volume 2, Revision 1 (NRC 2006), but reworked specifically for subsurface surveys. Nearly all the discussion of approach in MARSSIM and NUREG-1757 is appropriate.

Characterization surveys may be performed to satisfy a number of specific objectives, including the following:

- Determine the nature and extent of subsurface residual radioactivity.
- Evaluate remediation alternatives (e.g., unrestricted use, restricted use, onsite disposal, offsite disposal).
- Develop additional input to pathway analysis/dose or risk assessment models for determining site-specific DCGLs (pCi/g).

[17] A “small fraction” is not formally defined, but a definition is expected in future guidance.

- Estimate the occupational and public health and safety impacts during decommissioning.
- Evaluate remediation technologies.
- Develop input to the FSS design.
- Comply with other applicable regulations.

The technical aspects related to decommissioning of sites are often characterized as either “simple” or “complex.” The question becomes how to define these terms. The definition depends partly on what aspect of the decommissioning is being judged. If an elevated volume (hot spot) is identified near or clearly above the release criteria, a “complex” situation is apparent. Continuing site characterization may be complex at a site, but the FSS, after remediation, may be simple and straightforward.

Licensees typically submit site characterization information as part of their decommissioning plan (DP). The licensee may be asked to submit site characterization plans or other site characterization information before submitting the DP, or the NRC may elect to meet with the licensee before or during site characterization work. However, it is important to note that, unless required by a license condition, NRC regulations do not require licensees to submit a separate site characterization plan or site characterization report; rather, site characterization information is required only as a component of the DP. The NRC staff will request this information only when necessary to ensure safety and compliance with NRC regulations (NRC 2006).

The characterization survey is generally the most comprehensive of all the survey types and generates the most data. The survey includes preparing a reference grid, systematic as well as judgment measurements, and surveys of different media to include surface soils. Additionally, the characterization survey should identify all activated materials (typically Decommissioning Groups 4–7 described in NUREG-1757) and hard-to-detect (HTD) radionuclides throughout the site. The site-specific decision as to which media will be surveyed is addressed throughout the RSSI process (NRC 2006). Figure 5-15 presents the characterization survey portion of the RSSI process as updated to accommodate the AOC map, revised DCGLs, and CCM requirements.

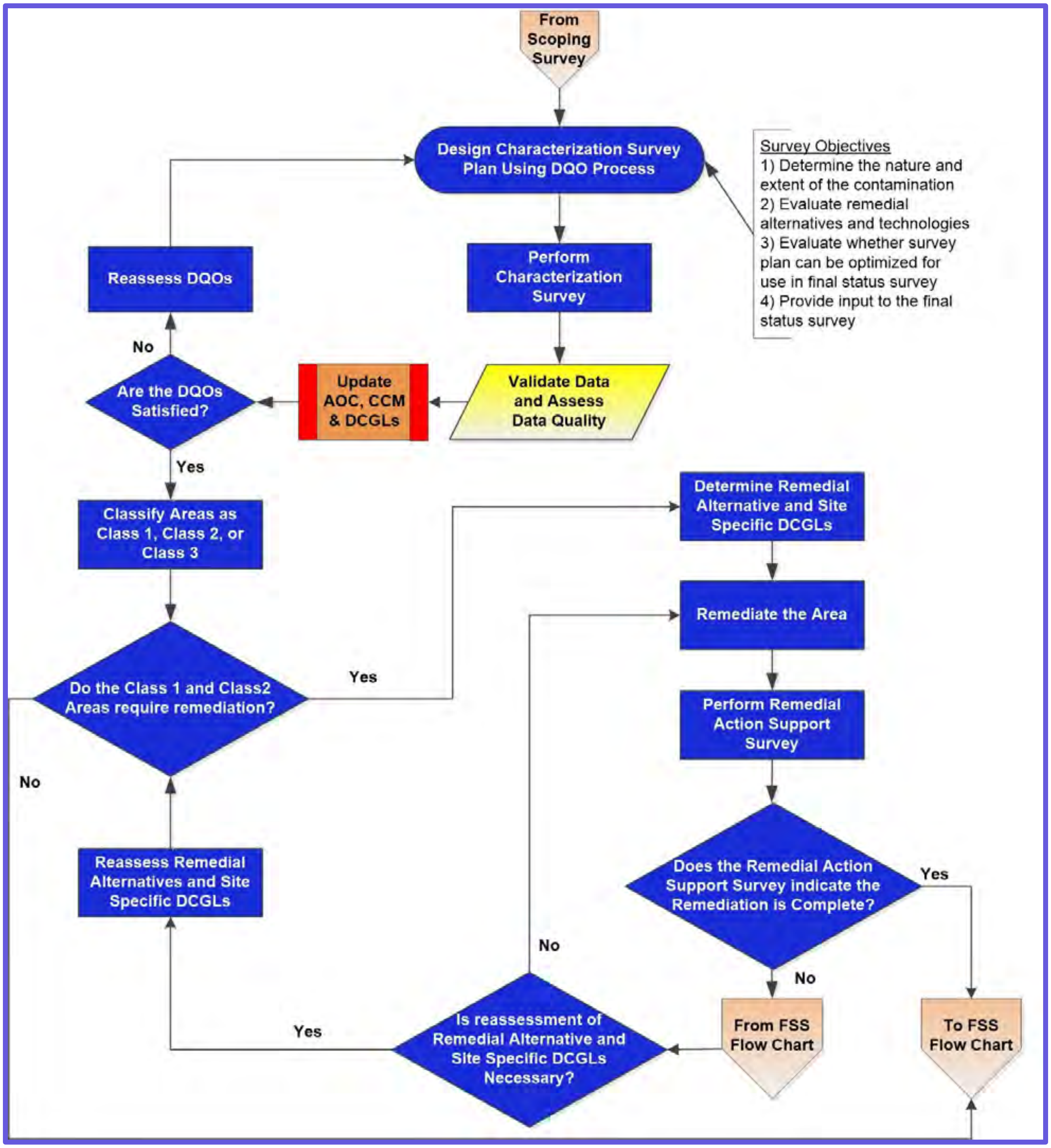

Figure 5-15 The Characterization and Remedial Action Support Survey Portion of the RSSI Process

Source: Updated from NRC 2000a

5.4.1 The Area of Concern Boundary Map

In this phase, investigators attempt to model the contamination event to estimate both the extent and volume of the contaminated media. A relevant design is the AOC boundary design. The

AOC is a spatial delineation of where concentration values may be too high and remedial action may be required. Using SADA or other software, risk assessors can estimate this area and also quantify the uncertainty about the location of the AOC boundary line (Stewart et al. 2009).

Following the scoping survey, additional samples usually are required to determine the extent and volume of the AOC. Of course, the more sample results there are, the better the delineation of the boundary. Advanced geospatial methods are available to delineate the AOC and associated uncertainties regarding the exact boundary location. This type of characterization approach can improve the efficiency of the characterization process and lead more rapidly to a remedial design phase. The outcome of this phase is (1) an updated CCM map and (2) an AOC map that will inform the remedial phase. For ground water applications, the AOC map may be synonymous with the source term delineation (NRC 2012).

The AOC map is based on the CCM and indicates those regions that may require some remedial action. Based on the decision threshold, one can estimate where the boundaries of the AOC should be, given the data at hand and the latest CCM. From these boundaries, one can also calculate volume and mass and include overburden (the clean soil on top of contaminated soil). Furthermore, one can also view uncertainty bands around the AOC. Stewart et al. 2009 discusses the AOC map within SADA 5, which is tightly connected with this framework and will serve as the focus of this discussion. The investigator is not required to use SADA or adhere to this particular AOC derivation (NRC 2012). Figure 5-16 is a 2D illustration of an AOC.

Scale—Areas within the AOC can contribute to a decision criteria failure at two different scales: *block scale* and *site scale*. At the block-scale level, if an individual cell value exceeds the decision criteria, it is included in the AOC. At the site-scale level, all blocks (grid cells) are sorted from highest to lowest modeled values. Beginning with the most contaminated block, the algorithm simulates the remediation of individual blocks from most to least contaminated until the average of all blocks no longer exceeds the decision criteria. Many interesting details are involved in developing the AOC, such as overburden calculations, benching angles, and density/mass considerations (see Stewart et al. 2009 for more information). Emphasized here is how AOCs are built through a grid-cell level classification that can retain the uncertainty in the CCM within the AOC map (NRC 2012).

Cell Classifications—This document applies three major grid cell classifications that make up an AOC. These classifications quantitatively report model knowledge and uncertainty related to point-wise exceedance of the DCGL (1) > DCGL, (2) ≤ DCGL, or (3) << DCGL. This classification may be expanded or changed to meet the licensee’s needs (NRC 2012).

NUREG/CR-7021, Section 7.2, contains several examples of an AOC (one is shown above in Figure 5-9) and describes both nongeostatistical and geostatistical methods to support this type of classification and uncertainty. The SADA user manual (Stewart et al. 2009) and NUREG/CR-7021 are recommended reading before using SADA.

Figure 5-16 is a bird’s-eye view of the surface.

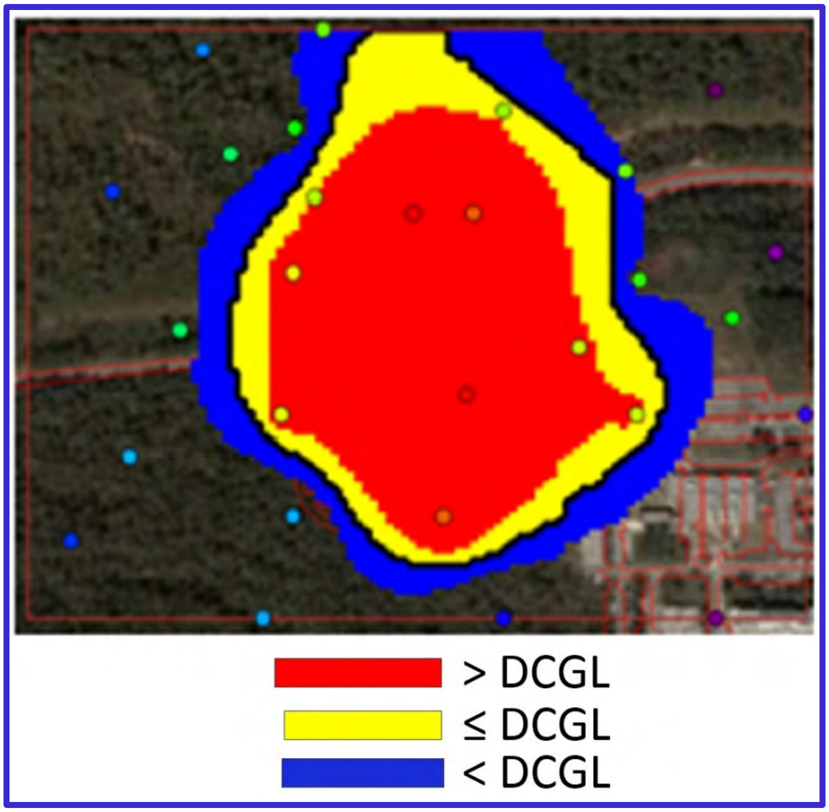

Figure 5-16 Example AOC Map

Source: NRC 2012

Considering that Figure 5-16 shows a need for remedial action, the licensee can choose to perform more characterization or move on to a remedial design (described in Section 6). The term "> DCGL" suggests that the sample results are greater than the $DCGL_V$, the $DCGL_W$, or both. If contaminated water is an issue, sampling should be instituted as indicated in Section 5.4.4.

5.4.2 Reference Grid and Coordinate System

Reference coordinate systems are established at the site to (1) facilitate selection of measurement and sampling locations and (2) provide a mechanism for referencing a measurement to a specific location so that the same survey point can be relocated.

A survey reference coordinate system consists of 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 (cells) of equal area; however, other types of patterns (e.g., 3D, polar) have been used (NRC 2000a).

The reference coordinate system used for a particular survey should provide a level of reproducibility consistent with the objectives of the survey. For example, a commercially available GPS will locate a position within tens of meters, while a differential GPS provides precision on the order of a few centimeters. On the other hand, a metal bar can be driven into the ground to provide a long-term reference point for establishing a local reference coordinate system (NRC 2000a).

Figure 5-9 above and Figure 5-17 below show example grid systems for outdoor land areas. In the example of a reference coordinate system for a survey of site grounds in Figure 5-17, Point A is identified as 100R, 2+00 (i.e., 200 m from the baseline and 100 m to the right of the baseline). Fractional distances between reference points are identified by adding the distance beyond the reference point and are expressed in the same units used for the reference coordinate system dimensions. Point B in Figure 5-17 is identified as 25R, 1+30 (NRC 2000a).

Open land reference coordinate systems should be referenced to a location on an existing State or local reference system or to a U.S. Geological Survey (USGS) benchmark. (This may require the services of a professional land surveyor.) GPSs can locate reference points in terms of latitude and longitude. Following establishment of the reference coordinate system, the survey team or the land surveyor prepares a drawing. This drawing indicates the reference lines, site boundaries, and other pertinent site features and provides a legend showing the scale and a reference compass direction (NRC 2000a).

The process used to develop the reference coordinate system should be recorded in the survey planning documentation (e.g., the QAPP). Any deviations from the requirements developed during planning should be documented when the reference coordinate system is established (NRC 2000a).

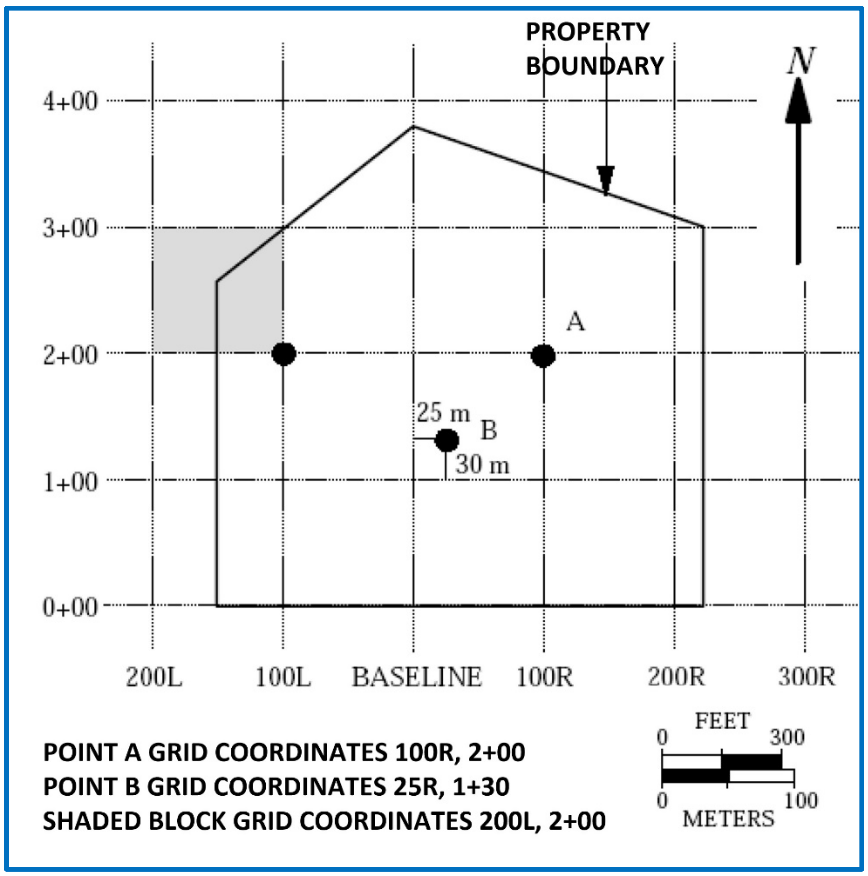

Figure 5-17 Example of a Grid System for Survey of Site Grounds Using Distances Left or Right of the Baseline

Source: NRC 2000a

5.4.3 Survey Design

The design of the site characterization survey is based on the specific DQOs for the information to be collected and is planned using the HSA and scoping survey results. The DQO process ensures that an adequate amount of data of sufficient quality is collected for the purpose of characterization. The site characterization process typically begins with a review of the HSA, which includes available information on site description, operational history, and the type and extent of contamination (from the scoping survey, if performed). The site description, or CCM as first developed in Section 2.5 consists of the general area, dimensions, and locations of contaminated areas on the site. A site map should show site boundaries, roads, hydrogeologic features, major structures, and other features that could affect decommissioning activities.

The characterization survey should clearly identify those portions of the site (e.g., soil and water) that have been affected by site activities and are potentially contaminated. The survey should also identify the portions of the site that have not been affected by these activities. In some cases where no remediation is anticipated, results of the characterization survey may indicate compliance with DCGLs established by the regulatory agency. In plans for the potential use of characterization survey data as part of the FSS, the characterization data must be of sufficient quality and quantity for that use. Several processes are likely to occur in conjunction with characterization. These include considering and evaluating remediation alternatives and calculating site-specific DCGLs. The survey should also provide information on variations in the contaminant distribution in the survey area. The contaminant variation in each survey unit contributes to determining the number of data points based on the statistical tests used during the FSS (Section 5.6). Additionally, characterization data may be used to justify reclassification for some survey volumes (e.g., from Class 1 to Class 2).

Because of the site-specific characteristics of contamination, performing all types of measurements described here may not be relevant at every site. For example, detailed characterization data may not be needed for areas with contamination well above the DCGLs that clearly require remediation. Judgment should be used in determining the types of characterization information needed to provide an appropriate basis for decontamination decisions.

5.4.4 Sampling Approach

When the DCGLs and surface areas for the EMC test with an acceptable site-specific dose assessment are established, the characterization survey is performed. Characterization data are used to identify the locations and general extent of residual activity. Data from the HSA and scoping surveys are used to guide the number and locations of core samples, using the CCM. Taking core samples to the achievable depth, a profile can be made of the residual radioactivity with 3D renderings.

- Samples within a core are separated into those less than background plus 2 σ (the cover), those greater than background plus 2 σ (the contaminated zone), and the uncontaminated unsaturated zone.
- In-field ISOCS or similar measurement of core sections is performed ≤1-m intervals.
- Radiation logging of borings is made usually at 30.5-cm (1-foot) intervals to establish depth of cover and depth to saturated zone. Borings should be both postextraction on the surface and downhole if possible.

- Laboratory samples of cores should be matched to in-field measurements and homogenized over a soil thickness that is consistent with assumptions made in the dose assessment, typically not exceeding 1 m in depth.

The described sample locations are for the most part biased locations by design, since the intent is to locate and characterize the extent of contamination (NRC2012).

5.4.5 Characterization of Surface and Ground Water

Characterization of surface and ground water is an essential component of the dose modeling used in the estimation of doses to demonstrate compliance with the license termination requirements in 10 CFR Part 20, Subpart E. Surface and ground water characterization should be planned to maximize the utility of the information to be collected and optimize its adequacy and quality during the characterization process. For example, a licensee may show for a particular site that the surface water pathway is not likely to be significant in terms of existing and potential future exposure to the public. In such a case, the need for detailed characterization of the surface water system is decreased. As an example of effective interactions during site characterization, identification of ground water contamination during the preliminary scoping survey may warrant installation and sampling of additional monitoring wells to define the extent and migration status of the contamination (NRC 2006). Two relevant review documents are Regulatory Guide 1.21, “Measuring, Evaluating, and Reporting Radioactive Material in Liquid and Gaseous Effluents and Solid Waste,” issued June 2009 (NRC 2009b), and NUREG/CR-6948, “Integrated Ground-Water Monitoring Strategy for NRC-Licensed Facilities and Sites: Logic, Strategic Approach and Discussion,” issued November 2007 (NRC 2007). NUREG/CR-6948 is a two-volume report, which presents a logical framework for assessing what, when, where, and how to monitor subsurface ground water flow and transport, so as to ensure that the environs of a licensed nuclear site or facility remain within the expected limits, as prescribed by the performance assessment.

In some instances, ground water may be unsuitable for specific uses, such as human and livestock consumption, but may be acceptable for crop irrigation. In addition, some aquifers may not have the yield to support crop irrigation but may produce enough water for human consumption. In some cases, the EPA or a State agency may have declared that the aquifer in question is unfit for human or livestock use. Accordingly, this type of information needs to be addressed since it will be used to support site scenario development and dose modeling (NRC 2006). If the water pathway is eliminated in RESRAD simulations, the resulting DCGL may increase for certain radionuclides.

The source area of a plume should be treated as soon as possible, if necessary to meet regulatory criteria, to avoid large expenditures to clean up residual radioactivity in the future. Delays can lead to a longer and more complicated cleanup (Abu-Eid 2012). At the time of decommissioning, it may be too late for cleanup as dispersion (e.g., tritium plumes) may have already occurred.

5.4.6 Evaluating Survey Results

Survey data are converted to the same units as those in which DCGLs are expressed. Potential radionuclide contaminants at the site are identified through laboratory and in situ analyses. Appropriate regulatory DCGLs for the site are selected, and the data are then compared to the DCGLs.

For characterization data that are used to help guide remediation efforts, the survey data are used to identify locations and general extent of residual activity. The survey results are first compared with DCGLs. Surfaces and environmental media are then differentiated as exceeding DCGLs, not exceeding DCGLs, or not contaminated, depending on the measurement results relative to the DCGL value. Direct measurements indicating areas of elevated activity are further evaluated, and the need for additional measurements is determined.

5.4.7 Documentation

Documentation of the site characterization survey should provide a complete and unambiguous record of the radiological status of the site. In addition, the report should contain sufficient information to characterize the extent of contamination, including all possible affected environmental media. This report should also provide sufficient information to support reasonable approaches or alternatives to site decontamination. An example characterization checklist from MARSSIM follows; the list has been modified slightly for subsurface characterization. NRC guidance must determine whether subsurface soils will be classified.

EXAMPLE CHARACTERIZATION SURVEY CHECKLIST

SURVEY DESIGN

_____ Enumerate DQOs: State objective of the survey; survey instrumentation capabilities should be appropriate for the specific survey objectives.

_____ Review the Historical Site Assessment for:

- _____ Operational history (e.g., any problems, spills, or releases) and available documentation (e.g., radioactive materials license).
- _____ Other available resources—site personnel, former workers, residents, etc.
- _____ Types and quantities of materials that were handled and where radioactive materials were stored, handled, and disposed.
- _____ Release and migration pathways.
- _____ Information on the potential residual radioactivity that may be useful for final status survey design. Note: Survey activities will be concentrated in Class 1 and Class 2 areas.
- _____ Types and quantities of materials likely to remain on site—consider radioactive decay.

CONDUCTING SURVEYS

_____ Select instrumentation based on detection capabilities for the expected contaminants and quantities and a knowledge of the DCGLs.

_____ Determine background activity and radiation levels for the area; include surface and ground water concentrations.

_____ Establish a reference coordinate system. Prepare scale drawing for surface water and ground water monitoring well locations.

_____ Perform systematic coring measurements for the classification.

_____ Perform systemic media and sediment surface water and ground water sampling, as appropriate.

_____ Perform judgment-based sampling of volumes of elevated activity of residual radioactivity to provide data on upper ranges of residual contaminate levels.

_____ Document survey and sampling locations.

_____ Maintain chain of custody of samples when necessary.

Figure 5-18 Example Survey Characterization Checklist

Note: Measuring and sampling techniques should be commensurate with the intended use of the data because characterization survey data may be used to supplement FSS data.

EVALUATING SURVEY RESULTS

_____ Compare survey results with DCGLs. Differentiate subsurface volumes as exceeding DCGLs, not exceeding DCGLS, or not contaminated.

_____ Evaluate all locations of elevated activity and determine the need for additional sampling.

_____ Prepare site characterization report; update DCGLs, AOC, CCM as needed.

Figure 5-18 Example Survey Characterization Checklist (Continued)

Source: Updated from NRC 2000a

5.5 REMEDIATION PHASE

As in the characterization phase, remedial activities can vary widely and are highly site specific. This section will again emphasize the role of data collected during the remedial phase with respect to the CCM. In some cases, as soil removal and processing occur, the soil is monitored in place as it is exposed and then removed. These are valuable measurements that can be used in updating the CCM, particularly the probabilistic CCM. This section concentrates on how to update the CCM and how to account for any soil remediation, removal, or replacement that may occur (Stewart 2012).

5.5.1 Remedial Sampling

In the course of soil remediation, additional samples may be collected as soil is removed or processed. These can be laboratory samples, field samples, or samples from secondary detection methods, such as gamma scans. This information can guide the removal process as it proceeds, but it can also update the CCM and AOC maps. By updating the CCM/AOC map with new information, new light may be shed on where and how far the contaminant may extend. Extent and severity estimates may adjust significantly as the process moves forward. Using this new information in the CCM, investigators can preemptively adjust budget planning if conditions differ drastically. In extreme cases, remedial activities may need to stop and characterization resume. The new samples provide more input to the CCM. The discussion continues by showing the effect of adding up-to-date remedial data to the CCM during the remedial process (Stewart 2012).

5.5.2 Updating the Contamination Concern Model

Based on the characterization phase’s AOC model, remedial boundaries are decided and soil removal conducted accordingly. During the soil removal process, a gamma count detector is normally used to estimate the residual radioactivity concentrations. As soil is removed, measurements are taken at various locations (Stewart 2012).

An example illustrates the value of 3D depictions of subsurface contamination before and after remedial activities. Figure 5-19 shows the artificial results for this example. The $DCGL_V$ is 18 pCi/g. Figure 5-19 presents 10 sample measurements per borehole. The sampling averaging volume would be based on the radionuclides present and the importance of smaller volumes of elevated activity.

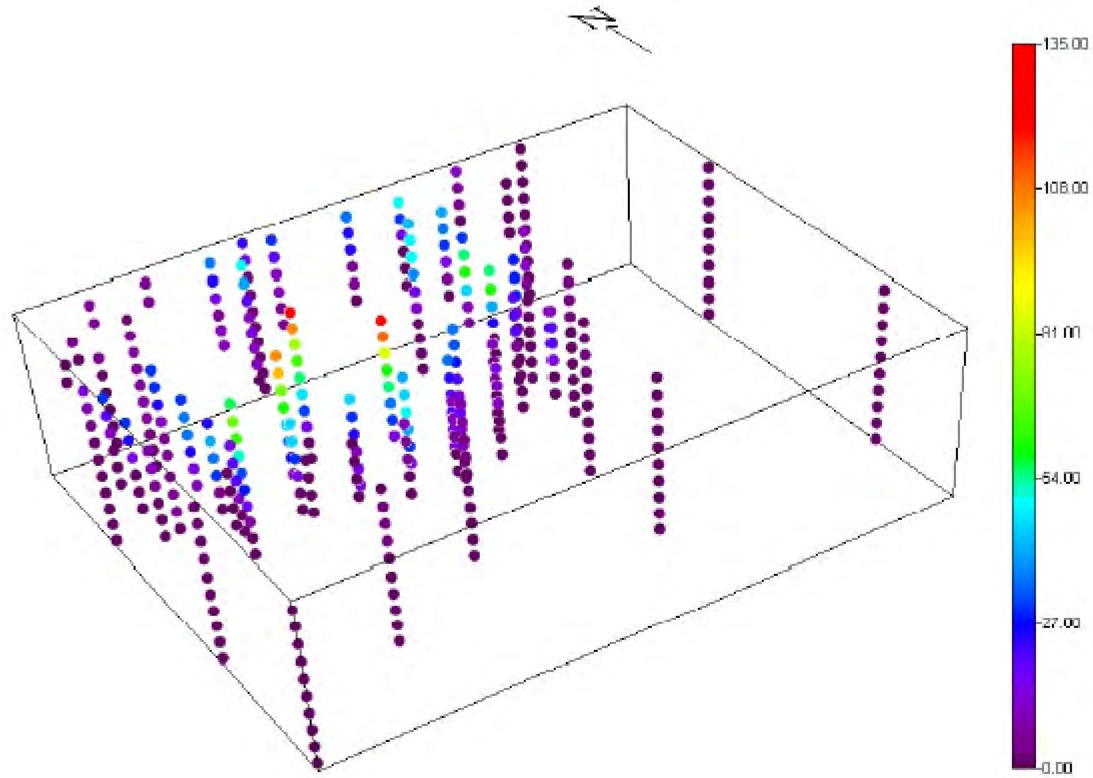

Figure 5-19 Example Pre-Remedial Sampling Results

Source: NRC 2012

Applying an indicator transform of the data can give a different perspective on these data. The $DCGL_V$ of 18 pCi/g is used to convert all measurements to either 0, if at or below 18 pCi/g, or 1, if above 18 pCi/g. Figure 5-20 shows the results.

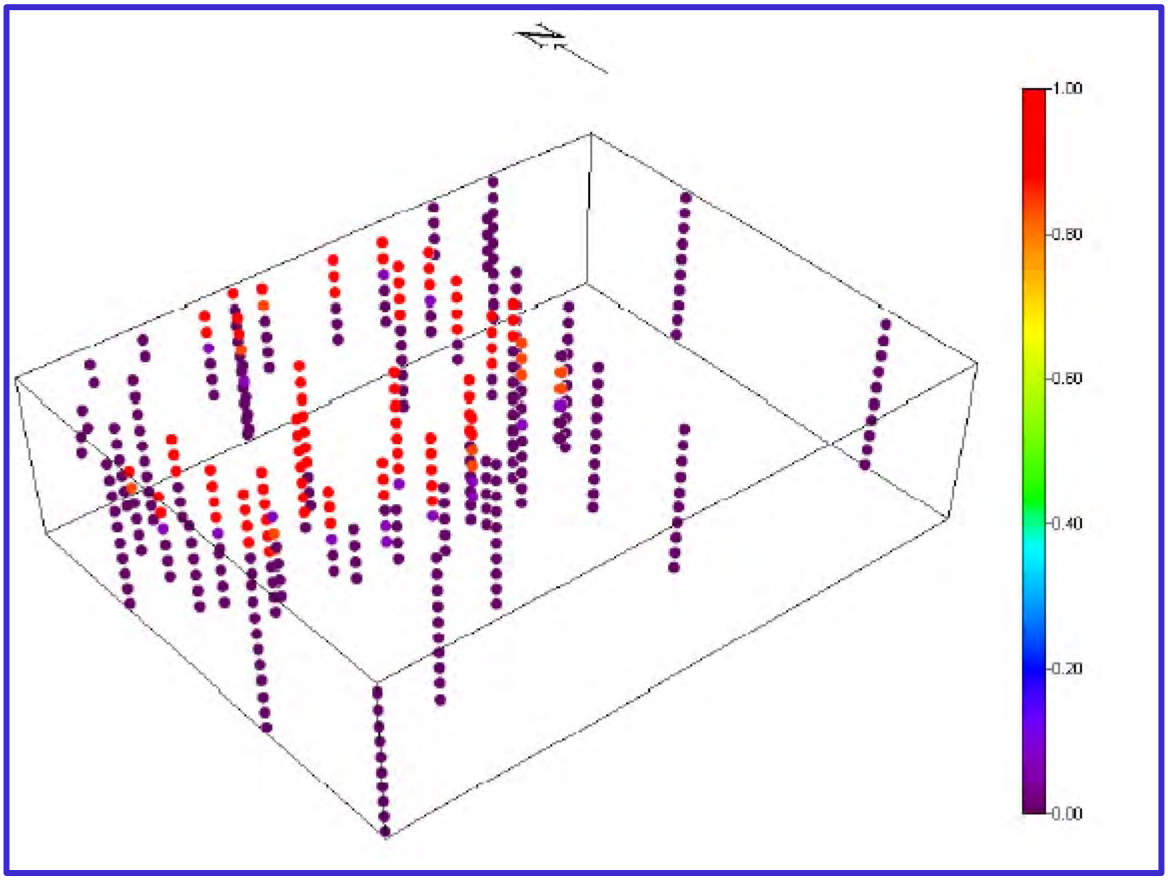

Figure 5-20 Indicator Transform of Measurements Based on a DCGL$_V$ of 18 pCi/g

Source: NRC 2012

One advantage of this approach is that it is easy to simply interpolate the probability values between sample locations. In Figure 5-21, the indicator values were interpolated using a simple inverse distance weighting method. This method was used to emphasize a potentially tractable approach accessible to a wide range of users. The indicator transform shares some features of the rank transform used in the MARSSIM WRS test. Some information is lost. If sample A is 17.9 pCi/g and sample B is 1 pCi/g, both receive an indicator value of 0. However, the indicator transform is resistant to outliers. If sample A is 18.1 pCi/g and sample B is 180 pCi/g, both receive an indicator value of 1. Regulators and other stakeholders will have a visual tool that can guide professional judgment during the remediation process.

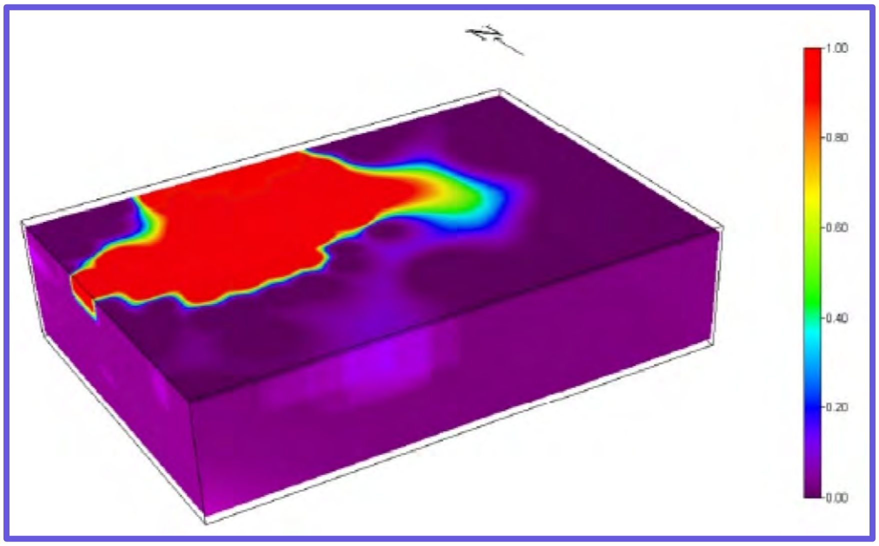

Figure 5-21 Spatial Model of Indicator Transformed Data Produces a Map of the Probability of Exceeding 18 pCi/g

Source: NRC 2012

Suppose most of the red area shown in Figure 5-21 was reportedly removed during remediation. If the originally contaminated area is replaced by a noncontaminated backfill, the area potentially remaining above the DCGL is seen in Figure 5-22 (NRC 2012).

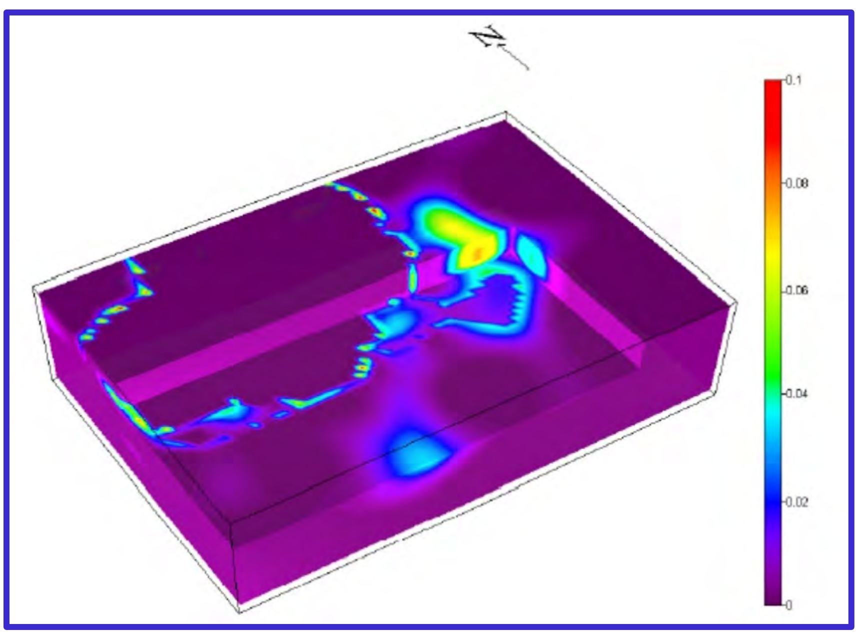

Figure 5-22 Post-Remedial Probability of Exceeding DCGL

Source: NRC 2012

The project may require further characterization, but when the stakeholders agree the contamination has been resolved, the compliance phase is entered. More samples will be collected in an FSS that may or may not demonstrate compliance. For the present example, the compliance phase is entered with all the available information collected for the site as evidence.

5.5.3 Surveys of Excavations

In cases where a licensee must remediate a site through excavation of subsurface with residual radioactivity above cleanup levels, several options are available to demonstrate compliance with radiological criteria for license termination. Although a backfilled excavation represents the final configuration of the site, it is a reasonable to expect that the licensee will perform the FSS on the open excavation before backfilling, if the survey can be performed safely. This is due to the potential cost and difficulty associated with adequately sampling a backfilled survey unit and the fact that scanning the entire depth of backfill would likely not be possible in most situations. Sampling and scanning of the open excavation also help to ensure that residual radioactivity above levels that would lead to an exceedance of the dose criteria are removed and appropriately disposed. When an FSS is performed on an open excavation, it is important to document the locations and depth range below final grade represented by sampling, as well as the general topographical layout of the excavation relative to final grade, to understand the final distribution of residual radioactivity at the site and to facilitate comparison to release criteria. Additionally, it is important to communicate with the NRC staff to plan confirmatory measurements of the excavation to independently evaluate radiological conditions before backfilling (NRC 2020b). NUREG-1757, Volume 2, Revision 2, provides specific guidance in Appendix G.

5.5.4 Surveys of Backfill Material

Revision 2 to NUREG-1757, Volume 2, also provides guidance on use of backfill from nonimpacted areas on site or from offsite locations. If the licensee is assuming there is no added residual radioactivity in the backfill, an analysis should be performed to support this assumption (i.e., that the backfill soils do not contain residual radioactivity). Residual radioactivity, as defined in NUREG-1757, includes radioactivity from all licensed and unlicensed sources used by the licensee, but excludes background radiation. On a case-by-case basis, the NRC has allowed reuse of soils from radiologically impacted areas as backfill at a site undergoing decommissioning. Licensees should continue to discuss proposed soil reuse plans with the NRC, as there are potentially complex issues associated with radiological measurement capabilities and site-specific dose assessments. Guidance in NUREG-1757, Volume 2, Revision 2, may assist licensees in developing reuse plans, though site-specific conditions may lead to additional issues (NRC 2020b).

5.5.5 When Ground Water Contamination Is an Issue

The NRC funded Brookhaven National Laboratory (BNL) to analyze its 13-year program of monitoring and modeling the tritium plume from the High Flux Beam Reactor and several strontium plumes from past operations at the Brookhaven Graphite Research Reactor. BNL documented this analysis of lessons learned in NUREG/CR-7029, “Lessons Learned in Detecting, Monitoring, Modeling and Remediating Radioactive Ground-Water Contamination,” issued April 2011 (NRC 2011b). The NRC technical staff working on recent ground water contamination at NPPs is applying these lessons. Figure 5-23 shows the basic steps in developing a remediation strategy (Nicholson et al. 2011).

As reported in the BNL study, lessons learned include (1) a well-developed process that ensures all elements are included in a risk-based remediation decision is needed, (2) facility monitoring is an important early line of defense in an environmental monitoring program, (3) it is important to understand the potential sources of contamination, (4) use of new techniques should be carefully planned and limitations fully understood before implementation, (5) initial efforts should focus on eliminating the source (once the source is eliminated, a more accurate estimate of life-cycle remediation needs and associated costs can be determined), (6) release of contaminants from the vadose zone, particularly mobile contaminants such as tritium, needs to be considered as a continuing source term, (7) hot spots for mobile contaminants in ground water should be removed as soon as possible since delays can lead to extensive and more complicated cleanup, and (8) site ground water modeling is an essential tool used to (a) evaluate remedial alternatives and (b) select design criteria including appropriate downgradient extraction well locations (Nicholson et al. 2011; Sullivan et al. 2011).

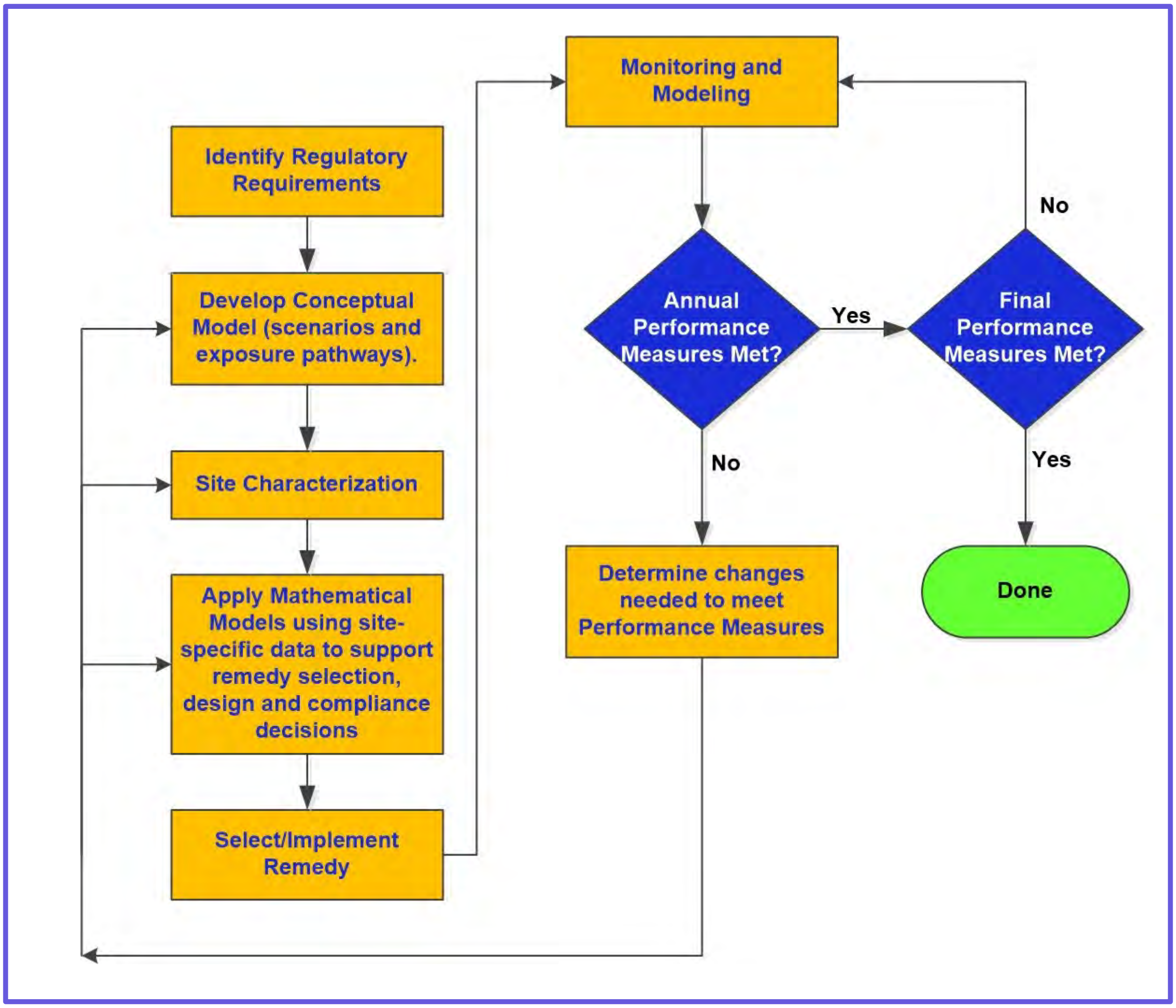

Figure 5-23 Remedial Action Process When Ground Water Is an Issue

Source: Nicholson 2011, Sullivan et al. 2011

5.6 FINAL STATUS SURVEYS

The FSS is used to demonstrate compliance with regulations. The development of objective statistical survey designs, sampling, analysis, interpretation, and statistical tests is the major focus of this report. The primary objectives of the FSS are the following:

- Select/verify survey unit classification.
- Demonstrate that the potential dose or risk from residual contamination is below the release criterion for each survey unit.
- Demonstrate that the potential dose or risk from small areas of elevated activity is below the release criterion for each survey unit.

The FSS provides data to demonstrate that all radiological parameters satisfy the established guideline values and conditions. Although the FSS is discussed as if it were an activity performed at a single stage of the site investigation process, this does not have to be the case. Data from other surveys conducted during the RSSI process—such as scoping, characterization, and remedial action support surveys—can provide valuable information for planning an FSS, provided they are of sufficient quality.

Professional judgment and biased sampling are important for locating contamination and characterizing the extent of contamination at a site (NRC 2000a, p. 2-24). If the survey data indicate that there is substantial subsurface residual radioactivity, and the licensee plans to terminate the license with some subsurface residual radioactivity in place, the FSS should consider the subsurface residual radioactivity to demonstrate compliance with the radiological criteria for license termination.

To prepare for the FSS, the characterization survey determines the depth of the residual radioactivity. In addition to conventional drilling, the licensee may consider the use of exploratory trenches and pits, where the patterns, locations, and depths are determined using prior survey results or HSA data (NRC 2020b).

Figure 5-24 presents the FSS portion of the RSSI process.

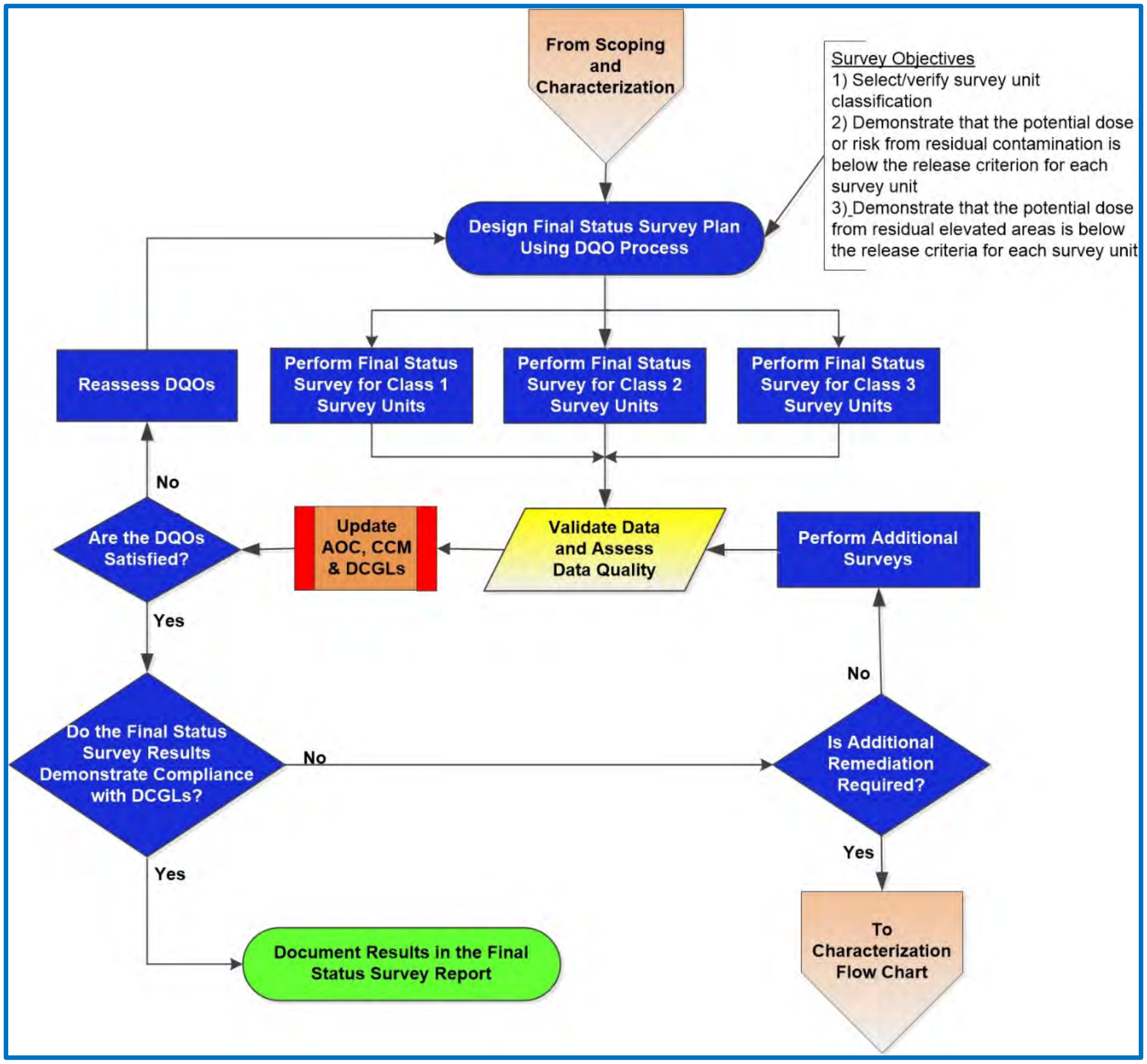

Figure 5-24 The FSS Portion of the RSSI Process

Source: Updated from NRC 2000a

5.6.1 Application of NUREG/CR-7021

Performing radiological surveys at sites with significant quantities of subsurface residual radioactivity is more complex than surveying surface soils because of the relative inaccessibility of the subsurface regions (e.g., subsurface soils cannot be scanned for elevated areas without the extraction of the materials). Additionally, heterogeneous materials are often encountered in the subsurface, and contaminated ground water may also present challenges to subsurface radiological surveys (see Appendix F to NUREG-1757, Volume 2, Revision 2). Because the MARSSIM methodology relies heavily on scanning to identify elevated AOCs, alternative or supplemental methods are needed when residual radioactivity is present in the subsurface. Modeling may help inform and supplement collection of radiological survey data and help alleviate the challenge of adequately characterizing the subsurface when scanning is not a viable option. NUREG/CR-7021 presents a framework focused on development of a CSM referred to as a “contamination concern map” (CCM). The CCM describes the extent, location, and significance of residual radioactivity relative to the decision criteria. The CCM can be developed with the aid of visualization, GIS, and geostatistical software. As additional data are collected, the CCM transitions from a mostly qualitative description to a more quantitative and detailed map. Subsurface concentration estimates and uncertainty measures serve as surrogates to scanning to facilitate better sampling designs and decision-making. The approach described in NUREG/CR-7026 presents one potentially acceptable method that may be used in conjunction with radiological survey data to demonstrate compliance (NRC 2012). For complex decommissioning cases where subsurface residual radioactivity and ground water contamination are present, it is important to work with the NRC early in the process to discuss acceptable approaches for demonstrating compliance with radiological criteria for license termination (NRC 2020b).

As discussed above, GIS and geostatistical software are available to assist with designing, performing, and evaluating the results of radiological investigations. GIS tools can help with the creation of conceptual models (e.g., by providing spatial context and a better understanding of site features that may control or enhance radionuclide transport in the environment). Figures created with GIS software can also assist with identifying relatively homogeneous areas of residual radioactivity for delineation of survey units (NRC 2020b).

For the FSS of subsurface soils, the MARSSIM methodology will need to be supplemented or an alternative methodology will need to be developed to demonstrate compliance with radiological criteria for license termination (MARSSIM addresses residual radioactivity only at the surface). Because the depth and thickness of residual radioactivity are correlated to dose, the modeling should reflect the actual distribution of radioactivity in the survey unit. For example, for certain radionuclides (e.g., those whose risk is dominated by the plant ingestion pathway), the thickness of residual radioactivity is strongly correlated to dose. If the dose modeling assumes a thinner layer of residual radioactivity than is present, then the risk could be significantly underestimated. If the dose modeling assumes a thicker layer of residual radioactivity than is present, then the risk could be significantly overestimated. For some radionuclides (e.g., those whose risk is dominated by the external dose pathway), the surface concentration may drive the risk as radiation emitted from residual radioactivity located at greater depth may be attenuated in the soil column and not contribute to dose. Therefore, if vertical heterogeneity is an issue, it may be necessary to take discrete samples to ensure that higher concentration residual radioactivity at the surface is not diluted in cleaner materials at depth. Dose modeling can be used to determine the sensitivity of dose to these parameters, and the soil sampling design should ultimately be consistent with the modeling used to develop the DCGLs. Ideally, sufficient resolution in the sampling data would be available to evaluate vertical heterogeneity and calculate appropriate concentrations for comparison against DCGLs derived for specific depths and thicknesses or for the total thickness of residual radioactivity to ensure that dose is not underestimated (NRC 2020b).

5.6.2 Integration of Dose Modeling and Radiological Surveys

Pathway dose or risk modeling is often used to determine cleanup levels or DCGLs used as decision criteria in statistical tests discussed in Chapter 8 of MARSSIM and Section 2 to NUREG-1757, Volume 2, Revision 2. Because DCGLs are an integral part of the survey design, consistency between the dose model and the survey design is an important topic discussed in various sections of the NRC guidance (NRC 2020b).

5.6.3 Number of Samples and Elevated Measurement Comparison

As the appropriate DCGLs have been estimated, based on an acceptable site-specific dose assessment, the FSS takes core samples to the measured depth of the residual radioactivity. As stated in Appendix G to NUREG-1757, Volume 2, Revision 2, the number of cores to be taken can be initially guided by the number (N) required for the WRS or Sign test, as appropriate. Using geostatistical methods may allow for a much lower sample density. A probability map, such as is generated by interpolated indicator kriging, can be used if the probability of exceeding the DCGL, rather than the actual value, is used as the parameter if interest in a decision rule. An AOC map may also guide the adjustment to the number of samples needed to detect an area of unacceptably high elevated activity.

Core samples should be homogenized over a soil thickness that is consistent with assumptions made in the dose assessment, typically not exceeding 1 m in depth. It is not acceptable to average radionuclide concentrations over an arbitrary soil thickness. Strict adherence to MARSSIM-type survey designs and statistical tests is likely to be an inefficient way to determine compliance. Other approaches, such as those illustrated in NUREG/CR-7021, should be considered. This would require development of survey designs and analyses based on criteria other than a simple comparison of data averages to a limit. A paradigm shift to more probabilistic measures may be more efficient.

Site-specific EMCs may also need to be developed to demonstrate regulatory compliance. These comparisons should consider key radionuclides, pathways, and exposure scenarios important to dose. For subsurface residual radioactivity at depth, the ground water pathway and total inventory may drive the risk (i.e., small elevated areas of concentration may not be important to dose). Most intrusion scenarios assume some minimum degree of mixing of excavated soils; therefore, mixing arguments can be presented when determining the minimum volume of soil of interest in developing EMCs (NRC 2020b).

5.7 OPTIMIZATION OF SAMPLING AND ANALYSIS

5.7.1 Analysis of Cores and Borings

The contaminated section of a core begins where field measurements are larger than the mean concentration from nearby uncontaminated regions of the same soil type, plus twice the standard deviation of the background measurements (Yu et al. 2001). If the concentrations in the samples used for determining the background concentration are below the lower limit of detection of the instrument used, the concentration of that radionuclide is considered to exceed background if it exceeds the lower limit of detection of the instrument (Yu et al. 2001). NUREG-1757 recommends 1-m intervals as a maximum thickness for sample homogenization, which will be used as the standard interval when possible. An analysis is required of contamination levels to a 3-m depth or more for an excavation scenario and a different analysis to the aquifer depth for an offsite evaluation.

If each subsurface soil core segment represents the same subsurface soil interval (e.g., 1 m), the average concentration from the surface to the depth of contamination is the simple arithmetic average of contaminant concentrations measured for core samples representative of each of the 1-m segments from the surface to the depth of contamination. However, if the sample intervals are not all of the same length (e.g., some are 61 cm (2 feet) while others are 30.5 cm (1 foot), the calculation of the average concentration in the total core must account for the different lengths of the segments (EPA 2000).

If C_i is the concentration measure in a core sample, representative of a core interval or segment of length l_i, and the nth segment is considered to be the last segment sampled in the core (i.e., the nth segment is at the depth of contamination), the average concentration in the core from the surface to the depth of contamination should be calculated as the depth-weighted average ($\overline{c}$) (EPA 2000).

Alternatively, the average boring concentration can be determined by adding the total contaminant activities together (from the sample results) for all sample segments to get the total contaminant activity for the boring. The total contaminant activity is then divided by the total dry weight of the core (as determined by the dry bulk density measurements) to estimate average soil boring concentration. Finally, the soil investigation for the migration to ground water pathway should not be conducted independently of ground water investigations. Contaminated ground water may indicate the presence of a nearby source area that would leach contaminants from soil into aquifer systems (EPA 2000).

5.7.2 Maximizing Data Available from a Core

The suggested method for sampling is conventional core boring and 1-m samples or smaller, which are readily defined. As described above and depending on the modeling, at least three data points can probably be made for each core by comparing in-field gamma rates to a laboratory result. However, in addition to core drilling for sampling, the licensee may consider the use of exploratory trenches and pits, where the patterns, locations, and depths are determined using prior survey results or HSA data (NRC 2006).

When the appropriate DCGLs and mixing volumes based on an acceptable site-specific dose assessment are established, the FSS is performed by taking samples (usually core samples) to the measured depth of the residual radioactivity. The number of cores to be taken is initially the number (*N*) required for determining the mean subsurface concentration unless geophysical data or geostatistical methods or both can be used to decrease that number without increasing decision error rates. The core samples should be homogenized over a soil thickness that is consistent with assumptions made in the dose assessment, typically not exceeding 1 m in depth. It is not acceptable to average radionuclide concentrations over an arbitrary soil thickness. The NRC has not yet developed generic guidance for performing an EMC for subsurface samples; therefore, licensees should discuss this matter with the NRC staff on a case-by-case basis (NRC 2020b).

The sampling approach described above may not be necessary if sufficient data to characterize the subsurface residual radioactivity are available from other sources. For example, for some burials conducted under prior NRC regulations, the records on the buried material may be sufficient to demonstrate compliance with the radiological criteria for license termination (NRC 2006).

5.7.3 Scan Minimum Detectable Concentration

What cannot be done for subsurface contamination from a MARSSIM perspective is a thorough check for elevated areas using scan technologies. Between sample locations, there is no means of collecting direct data measurements or comprehensive scan measurements, yet the demand for reasonable certainty is still high. Scans down boreholes can be conducted, but because of the physics of radiation, they will detect only a large amount of activity at a very limited distance (a few feet). The number of boreholes would then need to be increased geometrically to meet MARSSIM grade requirements (NRC 2012). The soil is its own shield, and the asymptote for exposure rate is reached within a few feet. Drilling cost would prohibit enough core holes to completely map a decision zone.

Scans of pulled cores may yield data regarding small elevated volumes or hot spots. However, core scanning will not provide data of sufficient quality to support subsurface FSSs; typical sodium iodide (NaI) scintillation detectors are expected to have high minimum detectable concentrations (MDCs). MARSSIM Section 6.7.2.1 discusses indication of high MDCs, and its methodology, along with Micro*Shield*, could produce MDCs for both downhole and cores (NRC 2000a).

5.7.4 ISOCS Alternative

The ISOCS (In Situ Object Counting System) is a gamma assay system and is an alternative to the collection of samples for laboratory analysis. By combining the detector characterization produced by the Monte Carlo N-Particle Transport Code (MCNP), mathematical geometry templates, and a few physical sample parameters, the system provides the ability to produce qualitative and quantitative gamma assays of many sample types and sizes, including subsurface cores. Some advantages of using ISOCS are the following:

- It is probably less expensive than sampling and laboratory measurements for subsurface sample measurements.
- It allows new measurements to be taken immediately to fill in data gaps or to resolve questionable data.
- Collimators can be used to reduce the influence of adjacent sources.
- For subsurface measurements,[18] the holes are lined with plastic pipe, and measurements are made at various depths down the hole, obtaining qualitative and quantitative results.
- It can measure core samples without mixing and homogenizing.

5.7.5 Use of Surrogates

When there is a fixed ratio among the concentrations of the nuclides, a compound $DCGL_W$ for each nuclide can be calculated that includes the contribution of the other radionuclides to the dose using the fixed ratio in place of its concentration. Compliance with the radiological criteria for license termination can then be demonstrated by comparing the concentration of the single surrogate radionuclide that is easiest to measure with its $DCGL_W$ (which has been modified to account for the other radionuclides present). For example, if cesium-137 and strontium-90 are present, using measured concentrations of cesium-137 as a surrogate for the mix of cesium-137 and strontium-90 may be simpler than separately measuring the radionuclides and may thus save labor and analytical expenses. When using a surrogate radionuclide to represent the presence of other radionuclides, sufficient measurements, spatially distributed throughout the survey unit, should be used to establish a consistent ratio between the surrogate and the other

[18] Mirion advertises that its In Situ Gamma Spectroscopy with ISOCS™ includes typical applications of determination of near-surface ground contamination and determination of subsurface contamination by "well logging." http://www.canberra.com/literature/gamma_spectroscopy/application_notes/InSitu-ISOCS-M2352.pdf

radionuclides. Section 4.3.2 of MARSSIM provides additional information on the use of surrogate radionuclides for surveys (NRC 2000 and NRC 2006.

In some cases when multiple nuclides are present with no fixed ratio in their concentrations, the dose contribution from one or more of the nuclides in the mixture will dominate the total dose, and the dose from other radionuclides will be insignificant. For example, at an NPP, many different radionuclides could be present with no fixed ratio in their concentrations, but almost all of the dose would come from just one or two of the nuclides. For guidance on elimination of radionuclides or pathways from consideration, refer to Section 3.3 of NUREG-1757, Volume 2, Revision 2.

Section 4.3.2 of MARSSIM provides additional information on the use of surrogate radionuclides for surveys. The responsible regulatory agency should be consulted before implementing this surrogate approach (NRC 2000a).

5.7.6 Composite Sampling

Composite sampling is a strategy in which multiple individual or "grab" samples (from different locations or times) are physically combined and mixed into a single sample so that physical, rather than mathematical, averaging takes place.[19] (EPA 2002a).

Appendix O to NUREG-1757, Volume 2, Revision 2, provides guidance on use of composite sampling, including information on when it would and would not be appropriate, derivation of modified investigation levels, and methods to incorporate composite sampling into survey designs.

Use of composite samples may be able to detect contamination over an area of concern (AOC) with a smaller number of analyses. Compositing involves pooling and homogenizing multiple soil samples. The composite is then analyzed to give an average value for soil contamination in that area. The following additional limitations on compositing should be observed:

- Compositing is most useful when large numbers of soil samples can be easily collected (e.g., for surficial contamination). To obtain the maximum information from deep soil coring, individual grab samples are preferred over composites.
- Compositing should not be used when analyzing soils for volatile organics because the constituents of interest may be lost during homogenization and sample handling (EPA 1989).

[19] The term "discrete sample" is often used to refer to an individual sample that is used to form a composite sample. For the purpose of this document, the terms "discrete," "grab," and "individual" sample have the same meaning.

6 GEOSPATIAL MODELING TOOLS

This section describes and evaluates geospatial modeling tools and currently available geostatistical software for analyzing contaminant distribution data and optimizing sampling, scanning, or otherwise obtaining information on the subsurface. These tools must be able to consider the likelihood of residual radioactivity above levels of concern and uncertainty associated with a dataset.

The statistical approaches used in MARSSIM have typically been applied to show that radiation dose-based site release criteria have been satisfied in surface soils and building surfaces. The methods used in MARSSIM continue to be used extensively in decommissioning guidance (e.g., in the 2009 European Commission report "European Radiation Survey and Site Execution Manual" (EURSSEM 2009). Consideration of subsurface contamination, when required, has involved the development of nonstandard, site-specific approaches. Recently, interest has increased considerably in using geostatistics for sampling plans and data analysis during decommissioning of nuclear facilities. While this has developed, the DQO process has been extended. The Triad approach described in Section 1 is one of these extensions. In addition, the EURATOM work program INSIDER (Improved Nuclear Site characterization for waste minimization in Decommissioning under constrained EnviRonment) was launched in June 2017 (EURATOM 2017). The objective of Insider Work Package 3 (WP3) is to draft a strategy for data analysis and sampling design for initial nuclear site characterization based on a statistical approach. Prior information (such as from an HSA), development of dynamic CSMs, adaptive sampling (as in Triad), testing the approach through case studies, and uncertainty calculations are considered. Figure 6-1a outlines the overall approach for Overall Strategy, Figure 6-1b for Data Analysis & Sampling Design, Figure 6-1c for Data Analysis Venn Diagram, and Figure 6-1d for a Sampling Design Venn Diagram (Desnoyers and Rogiers 2020). While the geostatistical methods mentioned fall under "Data Analysis" in these figures, several approaches have also been examined for using geostatistics to aid sample design, especially for secondary sample designs using data from prior surveys (Figure 6-1a).

Geostatistical tools can be used for radiological characterization of nuclear facilities during decommissioning and contaminated sites under remediation including sampling optimization, exploratory data analysis, and 2D and 3D maps of activity levels. This has prompted regulators worldwide to reexamine the handling of subsurface contamination in the verification of site release requirements. Two dissertations (Desnoyers 2010; Stewart 2011) have developed geostatistical tools for use in characterization sampling design and analysis for subsurface residual radioactivity. Stewart, as discussed further in Appendix M, primarily considers using geostatistics for subsurface soil in the unsaturated zone, while Desnoyers considers subsurface contamination in concrete building structures. In NUREG/CR-7021, Stewart extends the concepts in his dissertation to possible applications for ascertaining whether decommissioning has achieved residual radioactivity levels consistent with release criteria (Stewart 2012).

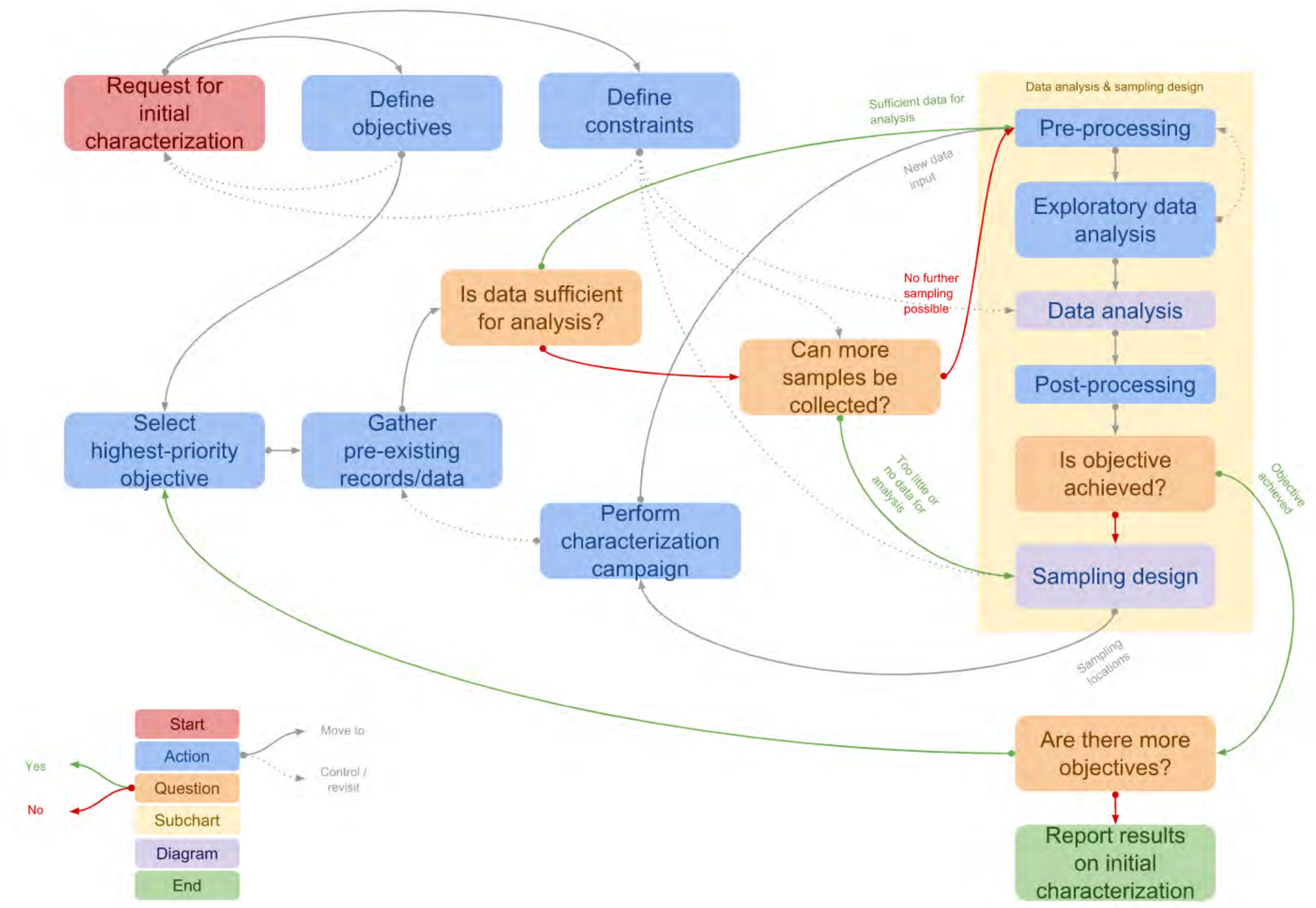

Figure 6-1a INSIDER WP3 D2—Overall Strategy

Source: EURATOM 2017

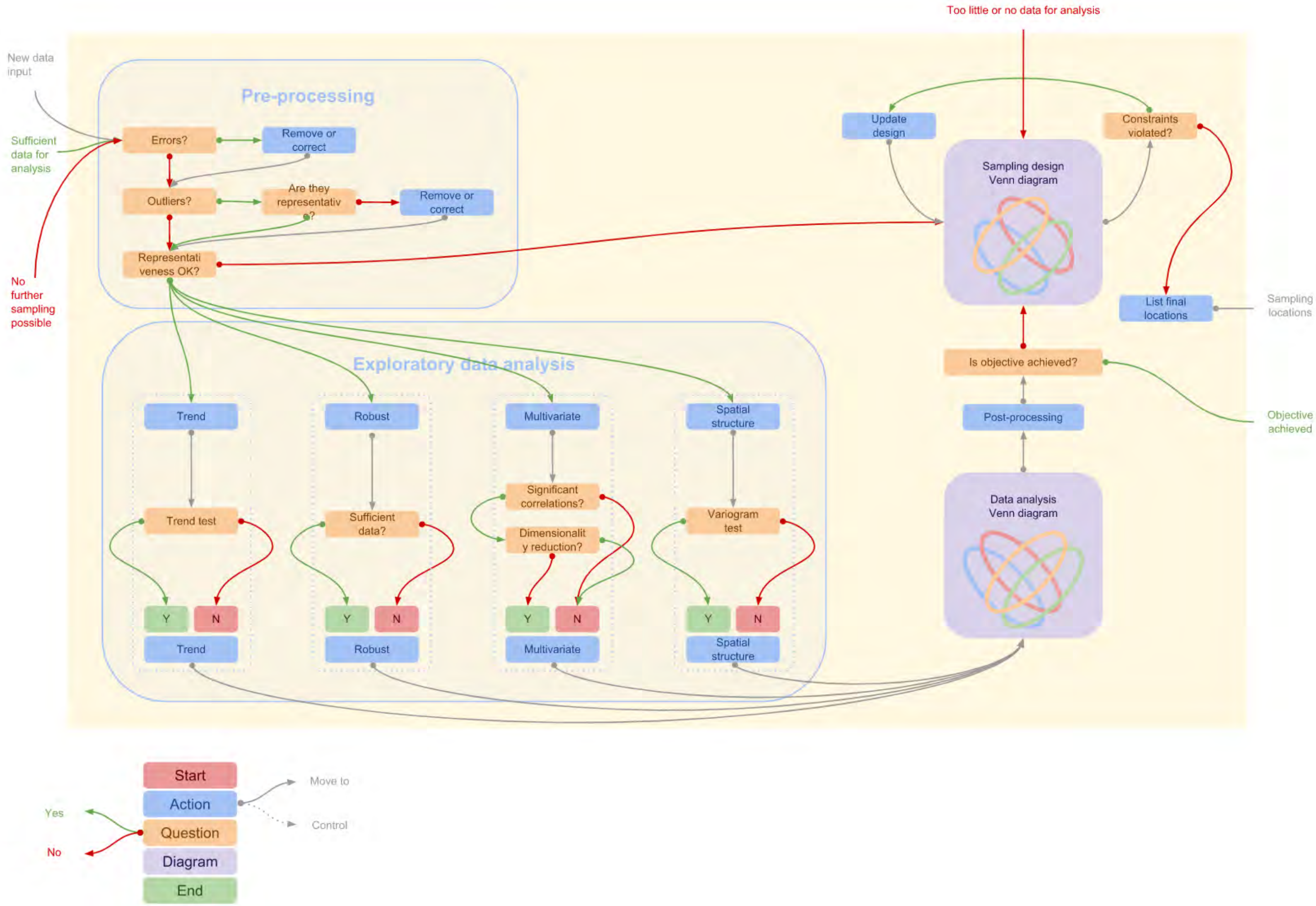

Figure 6-1b INSIDER WP3 D2—Data Analysis & Sampling Design

Source: EURATOM 2017

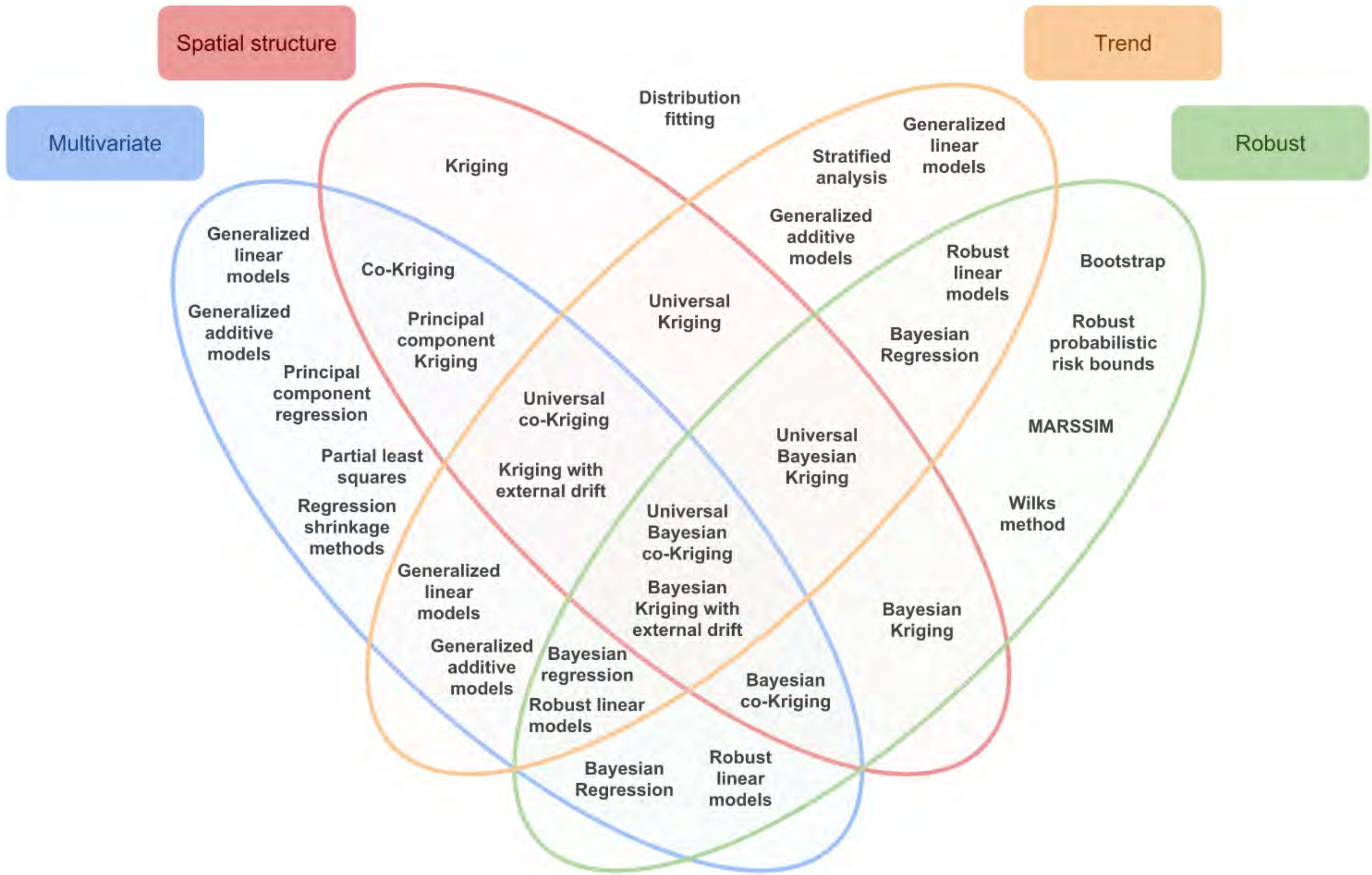

Figure 6-1c INSIDER WP3 D2—Data Analysis Venn Diagram

Source: EURATOM 2017

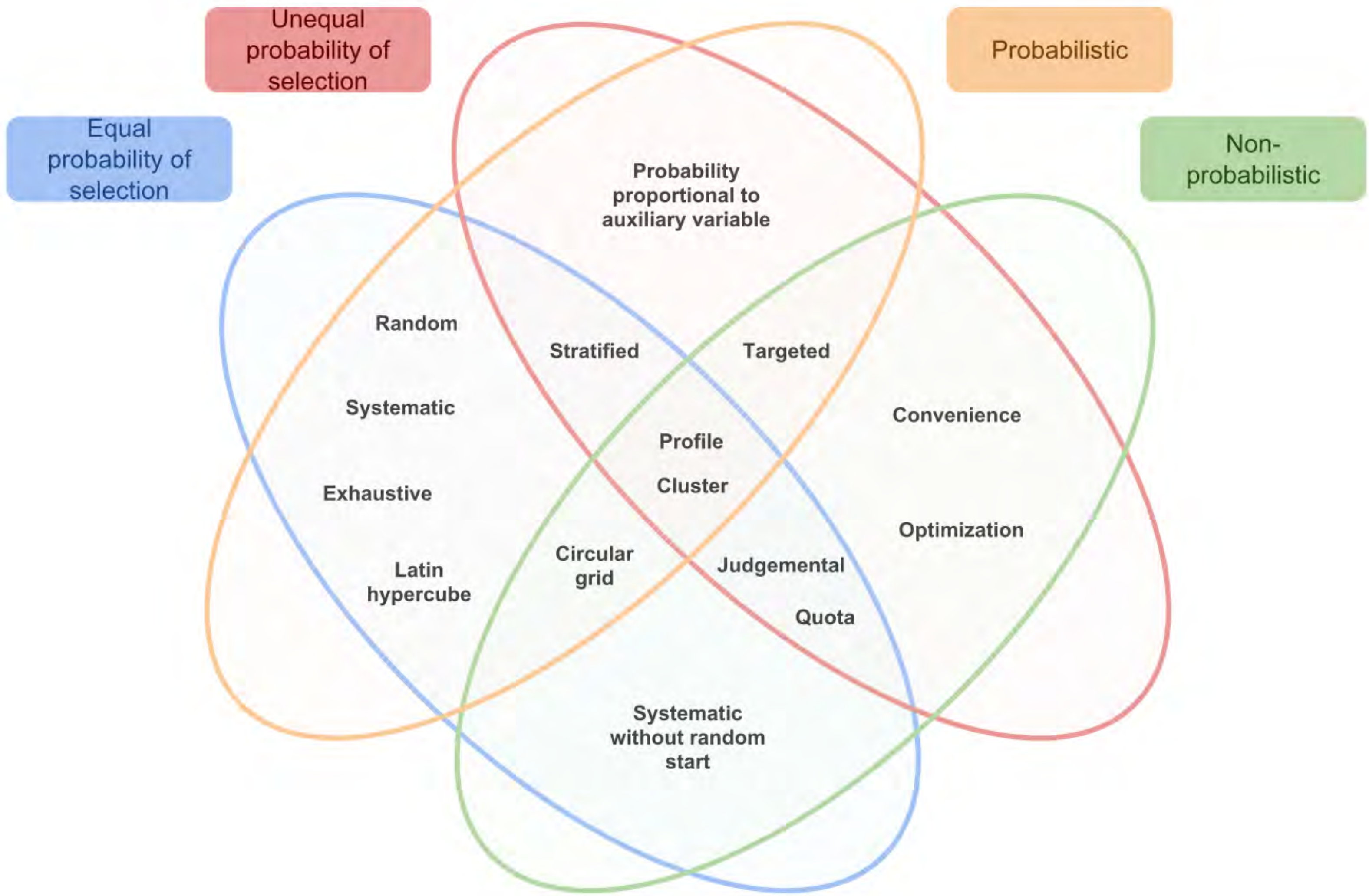

Figure 6-1d INSIDER WP3 D2—Sampling Design Venn Diagram

Source: EURATOM 2017

Many geospatial modeling tools are available. The Electric Power Research Institute (EPRI) sponsored EPRI Report 3002007554, "Guidance for Using Geostatistics in Developing a Site Final Status Survey Program for Plant Decommissioning," dated May 27, 2016 (EPRI 2016). The objective of this report is to introduce geostatistics and explain how it can help design characterization and FSSs for subsurface areas at NPPs. This report includes a comprehensive survey of existing tools for geospatial analysis, summarized in Table A.1 in Appendix A.

The book *Geospatial Analysis: A Comprehensive Guide to Principles Techniques and Software Tools* (de Smith and Longley 2020 and Web site https://spatialanalysisonline.com/software.html) contains many examples of geospatial tools. Table A.2 in Appendix A includes software listed in Geospatial Analysis Software Tools. Most of these tools require a knowledge of geostatistics and some computer programming. Most of these can deal with any quantity that varies in space, or time, or both. Any residual radioactivity or chemical contaminant can be analyzed.

Table A.3 of Appendix A presents a list of free software for analyzing geostatistical data, along with a list of software capabilities. The list is available from https://wiki.52north.org/AI_GEOSTATS/WebHome.

Goovaerts (2010) has also reviewed geostatistical software and suggests several criteria:

- Is access to the source code needed versus a black box? Is interactive variogram fitting preferred to an automated approach?
- Are the data collected in 2D or 3D? Does the sampling span both space and time?
- Are observations available at a limited number of discrete locations or over a large grid?
- Is the type of analysis a simple description of the major spatial pattern, a straightforward prediction at unsampled locations, or a more complex incorporation of secondary information? A modeling of local or spatial uncertainty?
- What is the level of geostatistical expertise of the user? Is user friendliness more important than flexibility? Is the analysis restricted to geostatistics, or does it involve sampling design and decision-making?

Table A.4 in Appendix A shows the software considered by P. Goovaerts (2010).

SADA (Stewart et al. 2009) can include some extensions for subsurface analyses. The extensions to SADA described in Stewart (2011) and NUREG/CR-7021 (NRC 2012) were never incorporated into SADA Version 5. The most important of these is the subject of Section 7 of this report and involves statistical methods to determine the necessary sample density, spatial distributions, depths and volume to achieve a certain level of confidence and limit decision error for subsurface contaminants during characterization surveys. Stewart (2011) refers to this as a "Check and Cover" survey design, which has two objectives:

(1) Check: Sample where contamination is known or suspected to exist.
(2) Cover: Provide some sample coverage across the rest of the site.

Figure 6-3 gives a workflow of the approach. As indicated above, SADA Version 5 is not capable of performing the Check and Cover design. This design depends on having a metric that can be used to estimate the value of each additional sample taken. The metric used in Check and Cover is called p-median (Ostresh 1978; Eiselt and Marianov 2019). The p-median is a numerical measure of the amount of information about the spatially likely location of contamination obtained by sampling. Figure 6-2 shows that the p-median metric decreases with the number of samples taken. Most of this decrease occurs with the first 10 samples; the curve flattens after about 20 samples. Hence, one can see a cost-benefit criterion for sample size. P-median is only one of many criteria that might be chosen, and it is important to note that it is not directly connected to any specified rates for false positives or false negatives in a hypothesis testing framework. Rather the p-median is a measure of the value of a sample at a given location in reducing the uncertainty in the probability of residual radioactivity exceedances at other locations across the site. NUREG/CR-7021, Section 6.2, gives further details. Other metrics should probably be considered when developing guidance for the number of samples and their locations. One may prefer a survey design alternative that specifies a given percentage confidence that a given proportion of the survey unit does not exceed certain subsurface residual radioactivity thresholds. Another criterion to be considered would be a specified probability that a threshold concentration for residual radioactivity at any grid point on a survey unit is exceeded. Such criteria might be closer in spirit to the MARSSIM tests for FSSs. Placing samples at locations to better determine the extent of contamination or to reduce the uncertainty in estimating it are additional criteria. Section 7 of this white paper considers these issues in greater detail.

Depending on the exposure scenario, important site parameters may be related to the 3D aspects of contaminant distributions. For example, the DCGL could be based on the inventory of contaminant in the soil, or its volume, rather than concentration. In this case, a larger volume may have a lower DCGL compared to a smaller volume with a higher DCGL, if the dose is related to total inventory. If related to the intrusion scenarios, such as a well driller scenario, the concentration in the volume brought to the surface and assumed to be mixed with clean soil may be important to dose, and therefore, the thickness and depth of contamination in the subsurface (which impact the amount of dilution with clean soil) may be more important than the total inventory. Dose modeling simulations would be important to better understanding the influence of various source parameters on dose and could inform metrics related to the number of samples that should be collected in the subsurface.

VSP should be considered essentially a 2D tool (Matzke et al. 2014). This does not automatically eliminate VSP from consideration for designing subsurface surveys. It will always be necessary to evaluate the number and placement of sample boreholes. The depth increments for these samples will depend on prior data and the HSA. These initial cores should be as deep as needed to identify the end of the contaminated layer. The depth increments of the cores should also be fine enough to determine the maximum depth of contamination and not average out too much detail at depth. These samples will be needed for the primarily judgmental scoping and characterization surveys. VSP also contains software for designing "transect surveys" (called scanning surveys in MARSSIM). These were developed for magnetometer surveys to determine locations of unexploded ordnance (UXO). However, they might be adapted to design scanning surveys with other geophysical measurement tools. These modules provide criteria for the amount of coverage required by scanning to achieve certain discovery criteria.

Any subsurface guidance to be developed would be greatly enhanced by a software tool to carry out visualization and survey designs of the subsurface. PNNL indicates that it has no immediate plans to take VSP to 3D (Wilson 2020); however, the infrastructure is in place to readily incorporate a third dimension in the suite of geostatistical tools available. Both SADA and VSP contain sample designs that have the objective of better defining the border (or contour) of residual radioactivity at a specified level. It may be that HSA or other prior data collected for seemingly unrelated purposes may be used in a preliminary CCM. In essence, these would serve as primary data for secondary survey designs intended for scoping and characterization. It is important to remember that scoping and characterization surveys are inherently judgmental.

In a private communication, Stewart (2020) updated SC&A on the present status of SADA. There is a partially developed SADA Version 6 in which some small advances were made, particularly in the 3D visualization, but it has not been released. There is no current support for maintaining or improving the code. SADA is based on Microsoft.NET and Fortran (GSLIB). Updating the code to more modern programming languages such as Python and R would be a substantial effort. R packages for geostatistics are listed in Appendices A, B, and C. It would still require much development to put these in a user-friendly form.

In MARSSIM, survey unit classifications are tied to the type of FSS performed. A Class 1 survey unit is ultimately defined as one that receives a Class 1 FSS up to a Class 3 survey unit, which is defined as one that receives a Class 3 FSS (the least rigorous). Thus, survey unit classifications can be subject to change until the FSS is designed. Nevertheless, the effort expended in scoping and characterization surveys should be appropriate to the expected final classification. There seems to be no compelling reason to have subsurface survey units (SSUs) strictly align with surface survey units. A Class 1 MARSSIM survey unit may overlie a Class 3 SSU. A Class 3 MARSSIM survey unit may overlie an unaffected subsurface unit. The boundaries (including depths) may not even be the same (e.g., if residual radioactivity is transported laterally in ground water or over a low hydraulic conductivity zone away from the source area). These aspects should be considered early in the DQO process for subsurface surveys. A Class 2 MARSSIM survey unit might overlie a Class 1 SSU, especially if clean fill were used to cover a low-level waste burial site. These considerations may have a profound effect on required sample sizes.

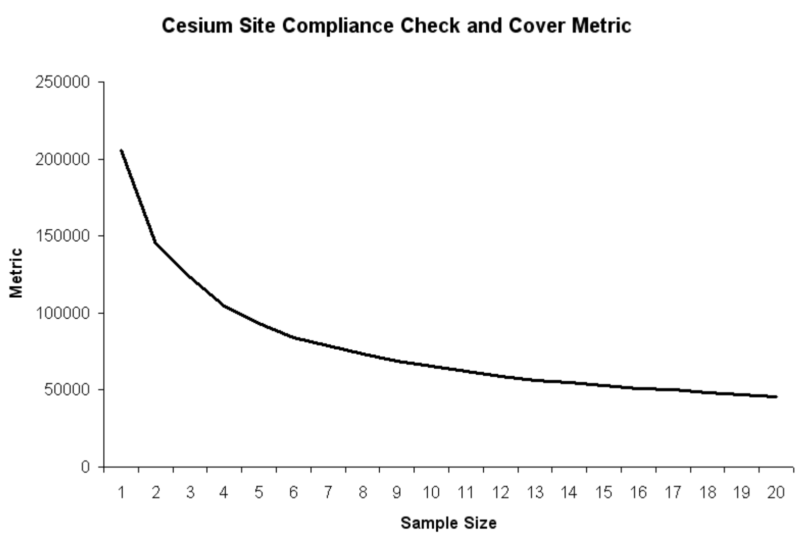

Figure 6-2 Check and Cover: Sample Size versus Design Metric

Source: Stewart 2011, p. 116

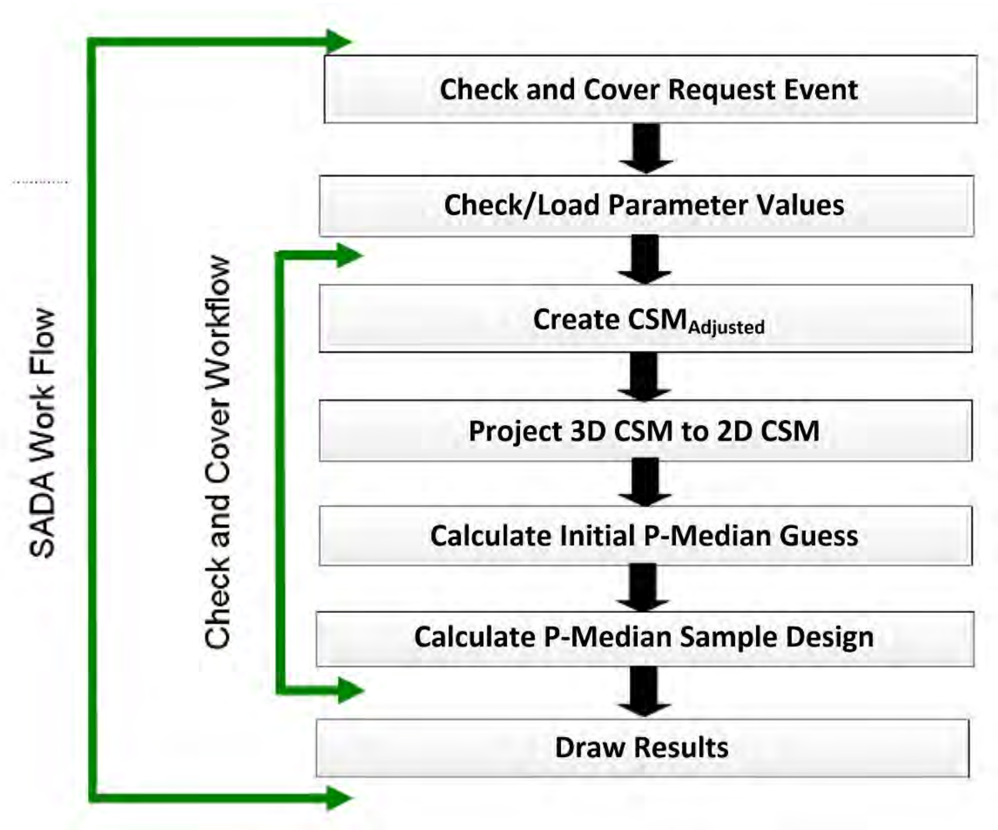

Figure 6-3 Check and Cover Workflow

Source: Stewart 2011, p. 122

Figure 6-3 shows the suggested workflow for a Check and Cover survey design. Note that this pathway includes a step for projecting 3D CSMs onto a 2D horizontal plane.

Any geostatistical kriging interpolation technique requires a fit to a variogram. Goovaerts (2010) noted this as one of the criteria for choosing a geostatistical software tool. The mechanisms for creating relationships among data points in the horizontal plane are primarily from deposition of material by air, dust, or spills. In the vertical dimension, data are likely to be related to transport from the surface, leakage from underground pipes, or deliberate burial. This situation would cause the scale of the variograms to be quite different in the horizontal and vertical. Variogram fitting generally requires a fair amount of data. These data are likely to be more available in the horizontal than in the vertical. Judging an adequate fit of a variogram model to the experimental variogram data requires some expertise in geostatistical methods. Rules of thumb can be used to develop initial estimates of a model variogram fit, which would often be adjusted by an experienced geostatistician. Guidance for using geostatistics for FSSs (statistical rather than judgmental) should consider how variogram fitting would be monitored and approved in regulations.

How readily these criteria would be accepted depends on how easily they are understood. Initial resistance to the application of MARSSIM for FSSs often took the form of questions such as "Why do we need statistics?" Education of users was important to MARSSIM acceptance, and the statistics involved were very simple standard tests. Possibly, suggestions for setting variogram parameters (such as nugget, range, and sill) can be tied to intuitive ideas (such as analytical uncertainty, distance at which one data point can be considered to influence another, and total analytical plus spatial uncertainty).

Kriging estimates are basically interpolations that weight nearer observations to a point more than those far away. How much more depends on the variogram used to calculate the weights. Thus, the numerical value of the variogram at small separations between data points is more important than the values at larger separations. Nevertheless, using some weighting of spatial correlations in the data is better than not using weighting at all. Sections 7 and 8 of this report will consider this topic in more detail.

Recognizing that the geostatistical software used in evaluating subsurface residual radioactivity would need to include sample design and data analysis capabilities, Sullivan (2002) reviewed environmental decision support tools. Table A.5 in Appendix A lists the software he considered. Two of these are user-friendly freeware tools that also give some latitude for adjusting how the sample and design analysis is performed. These are SADA and VSP, which have been discussed earlier in this section. Sullivan's conclusions are given in the next few pages. The most recent versions of these software tools also give the user the capability to design and analyze data from MARSSIM FSSs. For this reason, they stand out as being appropriate tools to use for subsurface survey designs and analysis. Both SADA and VSP have added features since the Sullivan report was published in 2002.

Section 5 of EPRI 3002007554 (EPRI 2016) also compares geostatistical tools but in much more detail (EPRI 2016). Section 5.1.6 discusses SADA, and Section 5.1.8 discusses VSP. Appendices B and C present these discussions.

SADA (Stewart et al. 2009)

From Sullivan (2002):

> ***Objective***
>
> Ultimately, the objective for Spatial Analysis and Decision Assistance (SADA) is to be a unified user-friendly software package that links practical environmental characterization tools to decision-making capabilities. SADA has the capability to integrate models for visualization, geospatial analysis, statistical analysis, human health risk assessment, ecological risk assessment, cost/benefit analysis, sampling design, and decision analysis.
>
> ***Advantages***
>
> SADA processes and produces information in a clear, transparent manner, directly supporting decision processes, and can serve as a communication tool between technical and non-technical audiences. SADA has a strong emphasis on the spatial distribution of contaminant data and is therefore best suited for anyone who needs to look at data within a spatial context, such as:

- Statisticians
- Risk Assessors
- GIS Users
- Project Managers
- Stakeholders

SADA is free software that incorporates tools from environmental assessment fields into an effective problem solving environment. The capabilities of SADA can be used independently or collectively to address site specific concerns when characterizing a contaminated site, assessing risk, determining the location of future samples, and when designing remedial action. A few examples of the types of problem SADA can address include:

- Calculate the volume or area of contamination above a clean-up threshold and present a site map with a map of contamination above a clean-up threshold on top of the site map.
- Calculate the area or volume requiring clean-up as a function of clean-up level and generate costs for remediation to the different clean-up levels.
- Select optimal sampling locations and place them on a site map.

The integration of the human health risk capabilities of SADA with modules for ecological risk assessment can help accomplish EPA's mission as outlined in the Ecological Research Strategy to: "develop and demonstrate a multiple pathway, multiple chemical model that integrates human health and ecological cumulative exposure and risk assessments." In addition, using the same problem solving environment for human health and ecological risk assessment assures consistency between the two assessment efforts in terms of the data that is used and the decision rules that are addressed. In this review, only the visualization, sampling design, and cost/benefit attributes of the code will be evaluated.

A fully functional freeware version is available on the download page of this web site. SADA was developed in the Institute for Environmental Modeling at the University of Tennessee. http://www.tiem.utk.edu/~sada/

A number of the capabilities present in SADA are also present in the FIELDS (Fully Integrated Environmental Location Decision Support) system.

Limitations

SADA integrates models from geostatistics with human and ecological risk assessments.

Background knowledge in these fields is essential to operating SADA properly when these models are used. Visualization in three dimensions is not as advanced as in other products. Some training covering the assumptions used in SADA and the databases supplied with the code are needed to optimally use the code.

SADA does not perform transient analysis to evaluate contaminant transport effects.

VSP (Matzke et al. 2014)

From Sullivan (2002):

> ***Objective***
>
> The purpose of Visual Sample Plan (VSP) is to provide simple, defensible tools for defining an optimal, technically defensible sampling scheme for characterization.
>
> ***Advantages***
>
> VSP is applicable for any two-dimensional sampling plan including surface soil, building surfaces, water body sediments or other similar applications. VSP provides statistical solutions to sampling design using state-of-the-art mathematical and statistical algorithms, and a user-friendly visual interface. VSP is designed to answer two important questions in sample planning.
>
> First: How many samples are needed?
>
> The algorithms involved in determining the number of samples needed can be quite involved and intimidating to the non-expert. VSP can quickly calculate the number of samples needed for various scenarios and estimate sampling costs.
>
> Second: Where should the samples be taken?
>
> Sample placement based on personal judgment is prone to bias. VSP instantly provides random or gridded sampling locations overlaid on the site map.
>
> Important features of VSP are that it:
>
> - Interacts with the user through familiar visual interfaces such as site maps and building plans.
> - Provides immediate feedback of the projected results of selected statistical sampling plans by overlaying random sampling locations or grids directly onto the site map or building plan.
> - Provides projected number of samples, total sampling costs, and sampling locations in appropriate coordinates.
> - Provides graphic decision tools such as graphs of probability of hot spot detection vs. total sampling costs.
> - Allows nonparametric and parametric sampling designs.
> - Generates MARSSIM supported sampling designs for soils and building surfaces.
> - Incorporates SampTOOL, a tool to guide the user to the appropriate type of sampling design.
>
> VSP is freeware that can be obtained at [https://vsp.pnnl.gov/].
>
> ***Limitations***
>
> The analyst should be familiar with statistical concepts to effectively use VSP.

VSP does not perform calculations of transport in the optimization of sample design. Therefore, it is best for contaminants that are immobile, or moving slowly with respect to the time between sampling and remediation.

7 STATISTICAL METHODS AND TESTS

This section describes the statistical methods to determine the necessary sample density, spatial distributions, depths, and volume to achieve a certain level of confidence and limit decision error for subsurface contaminants during characterization surveys. The MARSSIM statistical tests are evaluated for applicability, and alternative methods are proposed.

KEY POINTS

- The most promising methods for designing efficient subsurface surveys appear to be Bayesian Ellipgrid (geometrical) and Markov-Bayes (geostatistical). SADA implements both of these methods.
- The HSA can provide the prior information needed to use the Bayesian tools and thus should be as complete and accurate as possible.
- No single software package provides all the tools that would be desirable for subsurface sampling design and data analysis.
- VSP and SADA appear to have the set of features that may be most useful for radiological site surveys and investigations, although ProUCL also contains useful features.
- VSP is supported, maintained, and updated periodically with new features. SADA is available to download, but not currently supported or maintained or updated.
- SADA contains many features that are not normally used for NRC decommissioning problems and could be simplified to be specific to decommissioning.
- Both SADA and VSP have options to use only the MARSSIM parts of the code, but this would exclude any geostatistical operations. SADA does not implement MARSSIM Scenario B.
- Whatever software (or combination) is chosen, detailed written instructions and examples to demonstrate how they would be used in subsurface applications would be important.
- It may not be fruitful to expend great effort in calculating and fitting variograms.

7.1 INTRODUCTION AND THE IMPORTANCE OF THE HISTORICAL SITE ASSESSMENT

MARSSIM, Revision 1, Chapter 3, gives a general outline for performing a historical site assessment (HSA). In particular, Table 3-1 lists questions that may be useful for the preliminary HSA, and Figure 3-2 shows an example of HSA report format. Chapter 4 of NUREG/CR-7021 extends these concepts to the subsurface. Section 5 of this white paper discusses the HSA in detail.

Section 6 contains many geostatistical tools, but the most flexible seem to be the ones that require more expertise for their use. Among the many geostatistical sample design and data analysis tools, VSP and SADA have the set of features that may be most useful for radiological site surveys and investigations. Both programs assist in the design and analysis of MARSSIM FSSs. SADA covers only MARSSIM Scenario A. VSP has a rich array of mapping tools for interior spaces including doors, windows, and furniture. Such interior mapping tools may not be strictly applicable to subsurface surveys; they could conceivably be used to sample underground volumes (for example, caves or underground bunkers). While not a geostatistical tool, the program ProUCL (https://www.epa.gov/land-research/proucl-software) also contains features helpful in analyzing FSS data, including the Quantile test used in MARSSIM Scenario B. No single software package provides all the tools that would be desirable for subsurface sampling design and data analysis.

This section discusses how to design decommissioning surveys for a site with subsurface residual radioactivity. In MARSSIM, a major advance in survey design was achieved by effectively using information from HSAs, scoping surveys, characterization surveys, and remediation control surveys to design FSSs. Survey unit classification was a tool used to formalize a graded approach to decommissioning surveys. Attention is focused where the residual radioactivity is likely to be near or above a DCGL, also known as the action level (AL) or release criterion. A site map with survey units delineated and categorized as the foundation for release decisions is the CSM, as discussed in the Triad approach. A CSM uses all available historical and current information to estimate where contamination is located, how much there is, how the concentrations vary, how much spatial dependence is present, the deposition and transport contaminants in the environment, the critical group that may be exposed to residual radioactivity, and the pathways of exposure (see, for example, “Using Geophysical Tools to Develop the Conceptual Site Model,” issued December 2008 (EPA 2008)).

All prior information on potential residual radioactivity at the site will be collected at the HSA stage. This information can be applied to develop a contaminant concern map (CCM), as suggested in NUREG/CR-7021 (NRC 2012), which may be used to develop a subsurface decision model for supporting environmental compliance. This approach is essentially a formalization of a process in which information can be accumulated and summarized as data are collected and used to develop secondary sampling plans to eliminate important gaps in the data. The CCM summarizes the state of knowledge about residual radioactivity on the site and can be used to follow the evolution of survey unit classification as the survey units become better defined through a graded, adaptive approach.

SADA currently has the widest set of tools available for developing and maintaining a CCM for the site, but no single tool is now capable of performing all the required data sampling design and analyses. SADA is already capable of design and analysis in three dimensions by defining horizontal layers. VSP is fundamentally a 2D tool; although one might design vertical layers, they cannot be used to study data correlations in the vertical (Z-dimension) in geostatistical models. VSP does have 2D variogram fitting, which could be compared with those obtained with SADA, and 2D hotspot searching designs, which again might be compared with those from SADA. VSP also has quantitative sampling designs for scanning surveys that can incorporate DQOs for the probability of finding an elevated area of a given size by scanning, a capability not currently available in SADA. VSP is supported and maintained and has been subjected to verification and validation studies. SADA is not currently supported or maintained, nor has the code been verified and validated. This section discusses the design of decommissioning surveys as they might be supported by SADA and identifies possible alternatives. SADA is chosen as the focus based on previous NRC-supported work reported in NUREG/CR-7021.

SADA contains many features that are not normally used for NRC decommissioning problems. It would be worthwhile to produce a simpler version of the SADA user’s guide (Stewart et al. 2009) just for NRC decommissioning purposes. Both SADA and VSP have options to use only the MARSSIM parts of the code, but these do not currently include any geostatistical tools directly applicable to MARSSIM-type surveys.

The following are the main questions at hand:

- What can be done to determine the necessary sample density, spatial distributions, depths, and volume to achieve a certain level of confidence and limit decision error for subsurface contaminants during characterization surveys?

- What information is available for this task?

As mentioned previously, survey unit classification can begin with the information from the HSA (NUREG-1757, Volume 2, Revision 1, Appendix A, page A-3 (NRC 2006)):

> The presence of subsurface residual radioactivity is usually determined by the HSA (see Chapter 3 of MARSSIM), applying knowledge of how the residual radioactivity was deposited. Characterization surveys to detect subsurface residual radioactivity in soil are not routinely conducted unless there is reason to expect that subsurface residual radioactivity may be present. The need to survey or sample subsurface soil will depend, in large part, on the quality of the information used to develop the HSA, the environmental conditions at the site, the types and forms (chemical and radiological) of the radioactive material used at the site, the authorized activities, and the manner in which licensed material was managed during operations. [Appendix A, page A-3]

In addition, as stated in NUREG-1757, Volume 2, Revision 1, Appendix G, page G-6 (NRC 2006):

> The HSA will usually be sufficient to indicate whether there is likely to be subsurface residual radioactivity. If the HSA indicates that there is no likelihood of substantial subsurface residual radioactivity, subsurface surveys are unnecessary.
>
> If the HSA indicates that there is substantial subsurface residual radioactivity and the licensee plans to terminate the license with some subsurface residual radioactivity in place, the FSS should consider the subsurface residual radioactivity in order to demonstrate compliance with the radiological criteria for license termination. To prepare for the FSS, the characterization survey determines the depth of the residual radioactivity. In addition to conventional drilling, the licensee may consider the use of exploratory trenches and pits where the patterns, locations, and depths are determined using prior survey results or HSA data. The DCGL may be based on the assumption that the residual radioactivity may be excavated some day and that mixing of the residual radioactivity will occur during excavation. When the subsurface residual radioactivity is mixed and brought to the surface, most of the dose pathways will depend only on the average concentration. Only the ground water pathways are affected by the total inventory of residual radioactivity, including that deeper than 15 centimeters. The direct, inhalation, ingestion, and crop pathways are determined by concentration only, not total inventory.
>
> When the appropriate DCGLs and mixing volumes based on an acceptable site-specific dose assessment are established, the FSS is performed by taking core samples at least to the measured depth of the residual radioactivity. The

> number of cores to be taken is initially the number (*N*) required for the WRS or Sign test, as appropriate. The adjustment to the grid spacing for an elevated measurement comparison (EMC) is more complicated than for surface soils because scanning is not applicable. The core samples should be homogenized over a soil thickness that is consistent with assumptions made in the dose assessment, typically not exceeding 1 meter in depth. It is not acceptable to average radionuclide concentrations over an arbitrary soil thickness. The appropriate test (WRS or Sign) then is applied to the sample results. Triangular grids are recommended because they are slightly more effective in locating areas of concentrations. Site-specific EMCs may also need to be developed to demonstrate regulatory compliance. Generic guidance has not yet been developed for performing an EMC for subsurface samples; therefore, licensees should discuss this matter with NRC staff on a case-by-case basis.
>
> The sampling approach described above may not be necessary if sufficient data to characterize the subsurface residual radioactivity are available from other sources. For example, for some burials conducted under prior NRC regulations, the records on the material buried may be sufficient to demonstrate compliance with the radiological criteria for license termination.

Given the guidance in NUREG-1757, it is clear that the HSA is the first step in categorization and classification of the initial distribution of SSUs into those that are impacted versus those that are not impacted. As mentioned earlier, there is no a priori reason that SSUs align with surface survey units in size or shape.

The size limits for surface survey units as given in MARSSIM will need to be evaluated. Just as the $DCGL_V$ is likely to be different than the $DCGL_W$, the SSU classification may also differ. Sampling densities for SSUs do not necessarily conform to those for survey units, except for the fact that a core sample for an SSU will necessarily include a surface layer of 0–15 cm. This layer may or may not be analyzed, depending on the cost of the analysis and the perceived value of the information. The above paragraphs from NUREG-1757 on how core samples should be layered and analyzed require more detail from the dose model to determine that the sampling depth layers match the dose model assumptions. Scanning a core may also be possible if the scanning sensitivity is adequate. This is another issue that should be addressed in the subsurface guidance document. The output of this step should include a preliminary CCM.

7.2 SCOPING SURVEYS

Scoping surveys provide site-specific information based on limited measurements. Section 5.3 contains a detailed discussion of the importance and conduct of scoping surveys.

Scoping surveys are conducted after the HSA is completed and consist of judgment measurements based on the HSA data. Licensees should be aware that potential requirements of other applicable regulations (e.g., those concerning nonradiological constituents) may differ from NRC requirements. Appendix F to MARSSIM compares MARSSIM guidance to some other requirements. Scoping surveys consist of samples that are located by professional judgment and the HSA. MARSSIM, Revision 1, Chapter 5.2A, gives a general outline and checklist for performing a scoping survey. Chapter 6 of NUREG/CR-7021 extends these concepts to the subsurface. Scoping surveys should address any localized areas of previous significant incidents such as leaks, cracks, spills, or other unplanned releases of radioactivity. VSP has a module that aids in the design of geophysical data. This module was developed primarily to search for, find, and remove UXO. Within VSP, the geostatistical anomaly density mapping is composed of two primary tasks. The first task is to model the spatial variability of the measured anomaly densities as determined from the geophysical transect data. This task involves the development of a variogram based on the window-averaged transect density values.

Many environmental scientists are analyzing spatial data by geostatistical methods and interpolating from sparse sample data by kriging to make maps. Almost any spatially varying quantity can be interpolated using kriging. Kriging is an interpolation method in which the value being estimated is a weighted average of nearby data points. The sum of the weights is equal to 1, which means that it is an exact interpolator; that is, at the location of a data point, the interpolated value is exactly equal to the experimental value obtained. Kriging provides unbiased estimates with minimum variance. The method requires a plausible function for the spatial covariances through a variogram. A variogram depicts how the variability of a set of values changes as the distance between them increases. Constructing a variogram model requires the estimation of several important parameters, some of which are discussed below. The variability between values at two different locations increases as the distance between them increases to a *sill*, which is equated with the overall variance of the dataset. At zero distance, the variability of the data is essentially equal to the measurement uncertainty, called the *nugget*. The distance to reach the sill is called the *range*. The variogram must be estimated reliably and then modeled with valid mathematical functions. Appendix D outlines how to construct a variogram from experimental data.

As Section 11 will show, the measurement uncertainty is composed of the analytical measurement uncertainty and the subsampling uncertainty. It is the subsampling uncertainty that gave rise to the term “nugget effect,” because when two samples of a very inhomogeneous substance are taken, the value will depend on whether a “nugget” of activity (hot particle) is captured in the sample. It is important to note that at small distances between data points the variability is lower, so the values of the data at nearby sampling locations should be closer than those for data locations further away from each other.

An important part of scoping for subsurface residual radioactivity is the examination of buried pipes. It is especially important to inspect leaks from underground tanks or buried piping at nuclear sites during the scoping survey. Such tanks and piping may have been used for ancillary tasks such as water supply, and pipelines may have transported cooling water to the reactor and to spent fuel pools. They take steam to the main turbine, provide hydrogen gas to generators, supply fuel and lubricating oil to the emergency diesel generators, and much more. While they may be largely hidden from view, pipelines are used extensively within nuclear power plants, with the average reactor served by more than 7 miles of pipe (Day 2017).

During decommissioning when material is being removed, understanding what is inside the piping is key to the material’s safe removal. Leaks in piping may have caused unknown subsurface contamination. If radioactive material is present, activities such as cutting or grinding run high risk and may also spread radioactive material. Visual inspection (industrial endoscopy) is the first step in assessing a pipe’s condition. Features to observe are cracks, erosion, corrosion, debris, grinding, scouring, welding, manufacturing defects, discoloration, weld splatter (or spatter), location of insertions, and state of the coating.

7.3 CHARACTERIZATION SURVEYS

Section 5.4 contains details on characterization surveys; this section presents more information on the purpose and use of the CCM, number of required samples, and the potential use of VSP and SADA. Section 4 of NUREG-1757, Volume 2, Revision 1, states that after impacted locations have been identified, a characterization survey is performed to define more precisely the extent and magnitude of residual radioactivity. The characterization survey should be in sufficient detail to provide data for planning the remediation effort. A high degree of accuracy may not be required for such a decision. For any survey, the technique chosen should be commensurate with the intended use of the data as determined through the DQO process. It is not uncommon for traditional probability-based random sampling designs to make little or no use of any prior information. Options for survey design that make the best use of prior data to locate additional samples would seem to be the most efficient.

Prior expert judgment can be incorporated into survey design by using ranked set sampling, as described in Section 2.4.5 of EPA QA/G-5S/EPA/240/R-02/005, “Guidance on Choosing a Sampling Design for Environmental Data Collection,” issued December 2002 (EPA 2002c). Ranked set sampling designs identify sets of field locations, use inexpensive measurements to rank locations within each set, and then select one location from each set for sampling. Ranked set sampling is useful when the cost of locating and ranking locations in the field is low compared to more precise measurements. It is important that the ranking method and analytical method are strongly correlated. Ranked set sampling is available in VSP (see the VSP user’s guide, Section 3.2.3.2 (Matzke et al. 2014)).

This use of prior data is also often associated with Bayesian methods. Following the scoping survey, a CCM might be constructed to show where DCGL exceedances are likely. In SADA, this is called a “user-defined” model. There are two kinds of user models: standard and probabilistic. A standard user model allows the distribution of any kind of values (such as concentrations) over a site map. A probabilistic user model spatially expresses the probability of something being true or false (such as if the concentration at a location is likely to exceed a DCGL or not). Chapter 33 in the SADA user’s guide (Stewart et al. 2014) gives detailed instructions on how to use these tools. In essence, the user can “paint” values on a site map to reflect prior information. Figure 7-1 shows an example. In this figure, the site map is painted with colors corresponding to the rough estimate of the probability that contamination above the release criterion would be found at that location. This could be considered a very early attempt at a CCM.

With such a probabilistic model, it is possible to update the map of probabilities when real data become available. This is done using the Markov-Bayes geostatistical model (Goovaerts 1997), which is discussed further in Section 8. For now, it is an illustration of how expert judgment might be organized into a CCM. Suppose 28 samples are taken and analyzed. The probability map can be updated using the Markov-Bayes procedure implemented in SADA to give the new CCM shown in Figure 7-2. This new CCM may be further refined using AOC secondary sampling or used as a guide to remediation efforts.

But what if this CCM is wrong? One benefit of using the CCM is to highlight discrepancies. For example, if high activity levels are measured where they are not expected, many samples might be needed to update the CCM to better reflect reality. That is, data are needed to overcome the initial incorrect estimate of the probability of contamination in an area. Rather than take samples to move towards a better estimate, it would probably be wiser to revise the user model to capture the new process knowledge found in the data (NUREG/CR-7021, Section 9.6).

Figure 7-1 A User-Painted CCM Showing the User's Estimate of the Probability that the DCGL Will Be Exceeded in Samples across a Site as Shown in Color Scale

Source: Stewart et al. 2009, p. 417

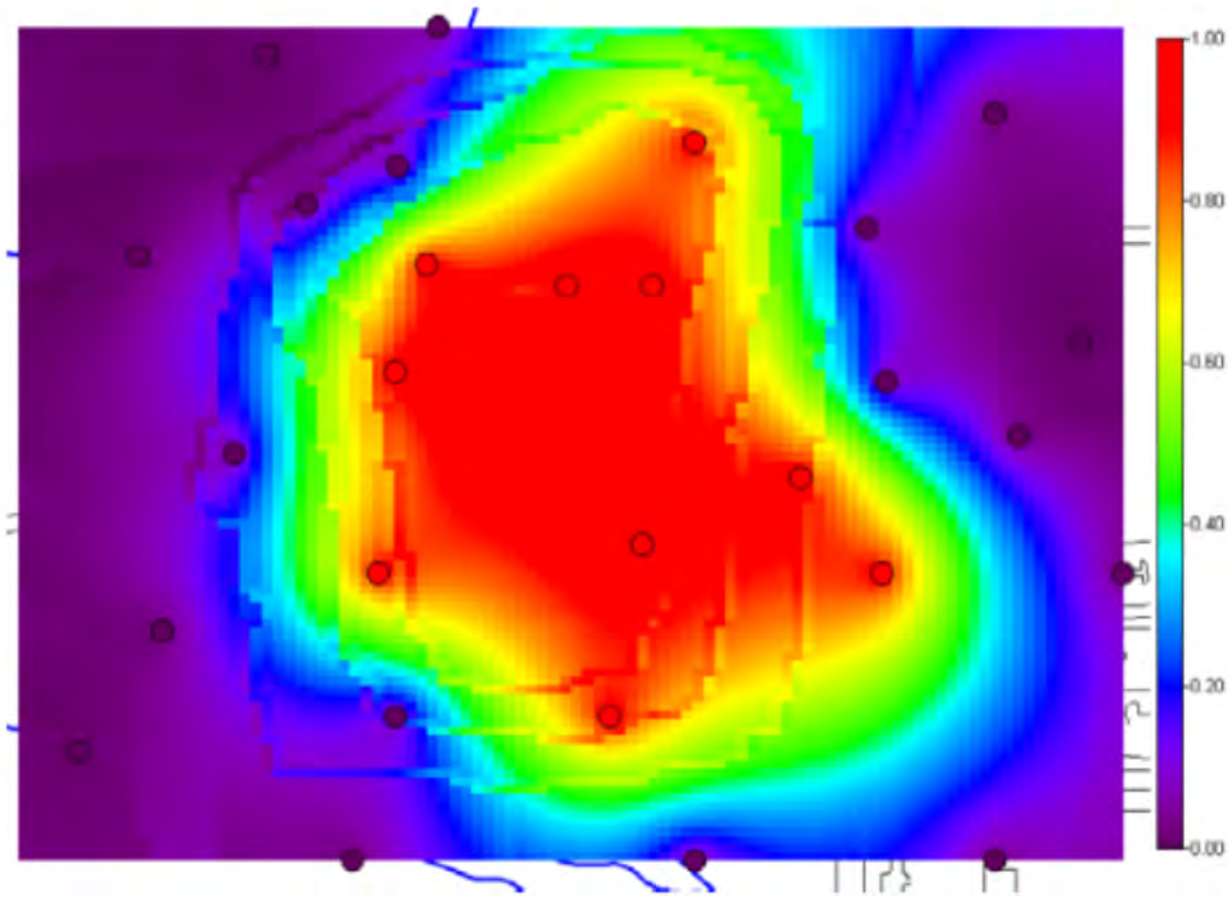

Figure 7-2 Markov-Bayes Updating of Figure 7-1 Using Data Obtained at the Circular Points

Source: Stewart et al. 2009, p. 422

For any survey design, a major issue is determining the number of samples to take. In MARSSIM, the number of samples is based on the desired limits on decision errors using the Sign or WRS test (supplemented as necessary to secure high probability of finding elevated areas above the $DCGL_{EMC}$). The Type I and Type II error rates are used to measure the value of taking additional samples. In MARSSIM, the power of the test is increased with additional sample data. The increase in power is the "return on the investment" of the cost of taking and analyzing additional samples. Sampling the subsurface will usually increase the costs of sampling, at least in terms of the depth at which the sample cores should be taken. Regardless of the depth of most interest, cores located at specified surface Northing and Easting coordinates will be taken. Processing and layering these into depth intervals will be necessary. Because sampling the subsurface is more costly, the design of subsurface surveys should include some measure of the value added to the decision-making process for each additional location sampled. Ideally, even at the characterization phase, the number of samples to be taken should be based on a metric that changes as the sample size increases. Therefore, a measure like the statistical power in MARSSIM is desirable. Such a measure is important to evaluate the adequacy of FSSs. To the extent that characterization surveys are used to assign survey unit classifications of SSUs from a compliance perspective, some evaluation of the site survey units during characterization would provide assurance that adequate data were obtained for this. SADA contains a number of metrics that could be used for this purpose.

NUREG/CR-7021 settles specifically on a Check and Cover process based on the metric p-median. As noted earlier, Version 5 of SADA does not take this approach. Even if available, the p-median metric would not necessarily be optimal or desirable for designing decommissioning surveys.

Another measure that might be used is the uncertainty expressed as the kriging variance. There has been some discussion in the literature about the appropriateness of using this uncertainty. Goovaerts (1997, p. 179) notes that ordinary kriging (OK) variance is dependent on the covariance model (variogram) and the data locations but it is independent of data values. Some researchers consider this to be an unattractive property and believe that the OK variance is merely a ranking measure of data configuration (Journel et al. 2000) rather than a full measure of uncertainty. However, this is one possible metric to use in survey design. It may be possible to locate samples so that the uncertainty measured by the kriging variance is minimized without knowing the values of the results. The kriging variance will depend mostly on the sample density near the point that is being interpolated. Since kriging is an exact interpolator, the OK variance will be low near a data location and high further away. A design based on this method will favor taking data near the polygonal boundary formed by the envelope of the sampling locations. That is, such a design will try to get more data where there are none. To be useful, the design would need to have a constraint that additional samples be located within a specified region of interest. It is not clear that the OK variance would be useful as a design metric or even as a measure of interpolation uncertainty.

Heuvelink and Pebesma (2002) have examined the issue of the OK variance, considering that it is the result of a derivation that is mathematically and statistically sound. They conclude that it is not necessarily true that interpolation error should be larger in areas where local data variation is larger, but that one can rely too much on the data in building a model of spatial uncertainty, and that it is important to decide whether the stationarity and Gaussian distribution assumptions are realistic. The choice that is made determines whether the simple kriging and OK variances are proper measures of interpolation error. Their simulation experiments showed that, even in the stationary Gaussian distribution case, local variation can be large. The results of their numerical experiment showed that the dependence between absolute prediction error and local spatial variation still was rather small for the lognormal case, even though the distribution was very skewed. A detailed discussion of this issue is beyond the scope of the present report; the information presented here is just to indicate the lack of universal agreement on the matter.

Wadoux et al. (2019) have looked at methods that optimize sampling schemes so that the data can better be used to estimate the variogram. OK variance is dependent on the covariance model (variogram) and the data. Spatial coverage schemes are often preferred, because they distribute sampling locations as uniformly as possible. Because the variogram is a measure of spatial correlation, the behavior of the variogram at small location separations will have a larger influence on interpolations than those further away. Nearby data are weighted more heavily in the kriging interpolation than those further away. Their results show a considerable benefit of adding close pairs to a spatial coverage scheme. They conclude that using a scheme in which 10 percent of the samples are taken at short distances is a robust strategy. This is reminiscent of the Check and Cover strategy in NUREG/CR-7021.

In MARSSIM, the number of samples is based on the desired limits on decision errors based on the Sign or WRS test (supplemented as necessary to secure a high probability of finding elevated areas above the $DCGL_{EMC}$). The supplemental requirement comes into play when the $DCGL_{EMC}$ is lower than the scanning method is able to detect (the scan MDC). The number of samples on the survey unit grid is increased until the grid area $DCGL_{EMC}$ is lower than the scan

MDC. Suppose, however, that the ROC is extremely difficult to measure by any scanning method (perhaps it is a low-energy beta-emitter with no suitable surrogates.) In MARSSIM, it is assumed that a circular elevated area with the size of the grid area inscribed in the space between grid locations has virtually a 100-percent chance of detection. This was determined by Ellipgrid calculations given in MARSSIM, Appendix I, Table I.5, but is not explicitly discussed in either MARSSIM or NUREG-1505, Revision 1, “A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys,” issued June 1998 (NRC 1998a). One potential solution is to reexamine what the smallest credible elevated volume of concern might be based on an analysis of data or dose modeling or both, and the probability of detecting it on the systematic sampling grid. This calculation can be done in both VSP (Chapter 3.2.5 in the VSP user’s guide (Matzke et al. 2014)) and SADA. Table 7.4 shows a VSP example. The SADA user’s guide discusses hot spot search strategies in the context of initial sample designs in Chapter 39 and the concept of the Bayesian Ellipgrid in Chapter 41 (Stewart et al. 2009).

A better strategy might be to use an approach that starts with a survey design for finding elevated areas rather than a statistical test. Defining the size of the elevated area and the size of the sampling grid in Ellipgrid results in a geometric probability of detecting the elevated area with a given number of samples. Figure 7-3 shows the Ellipgrid target geometry. The angle theta indicates the orientation of the elevated area to the sampling grid, and the ratio of the minor to the major axis defines the shape of the elevated area. Usually, no information will be available about a particular shape and orientation, so MARSSIM assumes that the shape parameter is one (i.e., the elevated area is approximately a circle and so the orientation angle is irrelevant). The probability of detecting the hot spot will increase with the number of samples and thus will provide a metric for the value of adding samples. Once an elevated area is detected, a more detailed statistical survey design can be used to evaluate the mean residual radioactivity. This strategy reverses the order in MARSSIM, in which the sample design for the mean is done first and adjusted for elevated areas later.

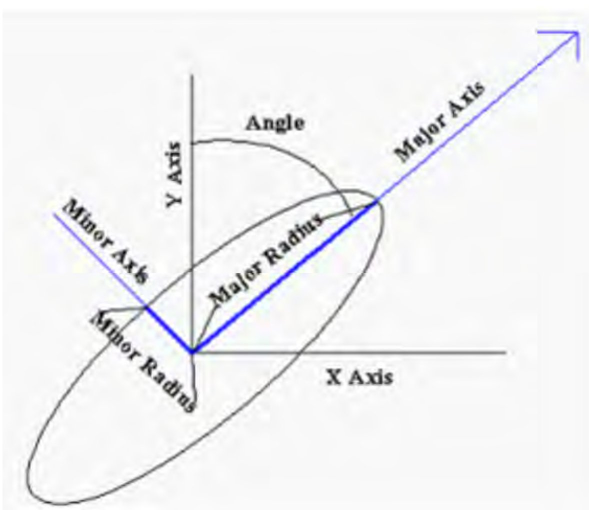

Figure 7-3 2D Elevated Area Geometry Used by the Ellipgrid Code

Source: Stewart et al. 2009, p. 281

Figure 7-4 shows the input dialog from VSP for finding the grid spacing for samples necessary to detect an elevated area of a given size and shape with a given probability (i.e., it focuses on the elevated area first and sampling for the mean second).

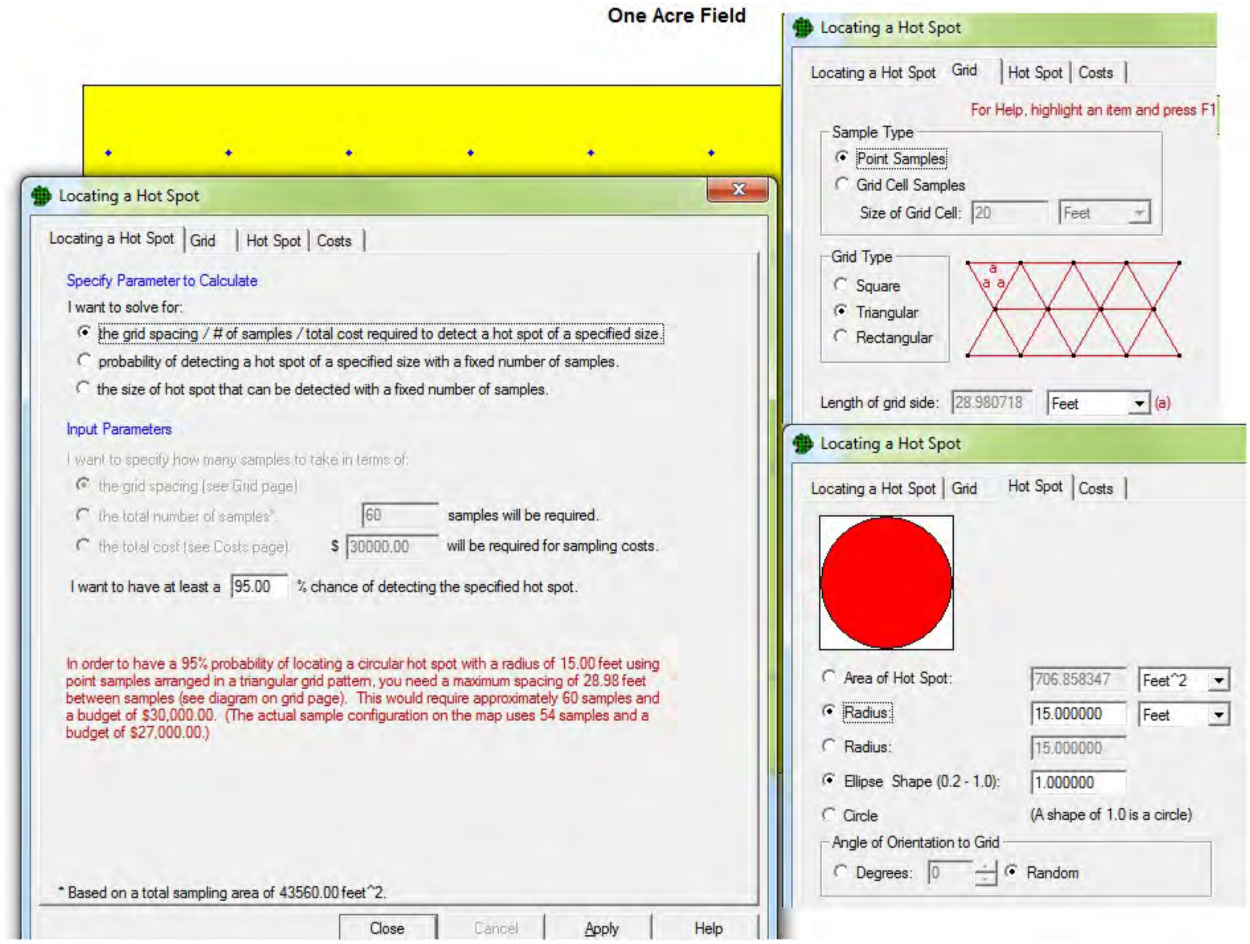

Figure 7-4 Input to VSP for Locating a Hot Spot

Source: Matzke et al. 2014, Figure 3.32

For both the Markov-Bayes and Bayesian Ellipgrid, a user-defined model is the starting point. Chapter 33 of the SADA user's guide (Stewart et al. 2009) discusses user-defined models in great detail. This includes 3D user models for subsurface residual radioactivity. Section 12 of this report discusses some of the approaches to evaluating elevated areas or hot spots in consideration of potential doses to receptors, including the inadvertent intruder. In this section, the design of an initial survey with a search for elevated areas is discussed.

Figure 7-5 shows a user-defined probability model, which expresses professional judgment concerning the existence of subsurface contamination across an entire site. It does not necessarily require very detailed information. It is essentially a more quantitative application of the graded approach involved in survey unit classification. Appendix E to this white paper gives details for completing this example. Figure 7-6 shows the input to SADA for the Bayesian Ellipgrid example.

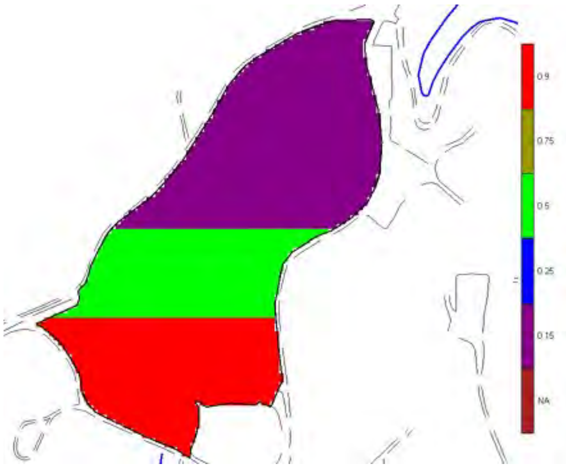

Figure 7-5 Probability Map Constructed for the Bayesian Ellipgrid Example Indicating the Likelihood of an Elevated Area in Various Parts of the Site

Source: Stewart et al. 2009, p. 542

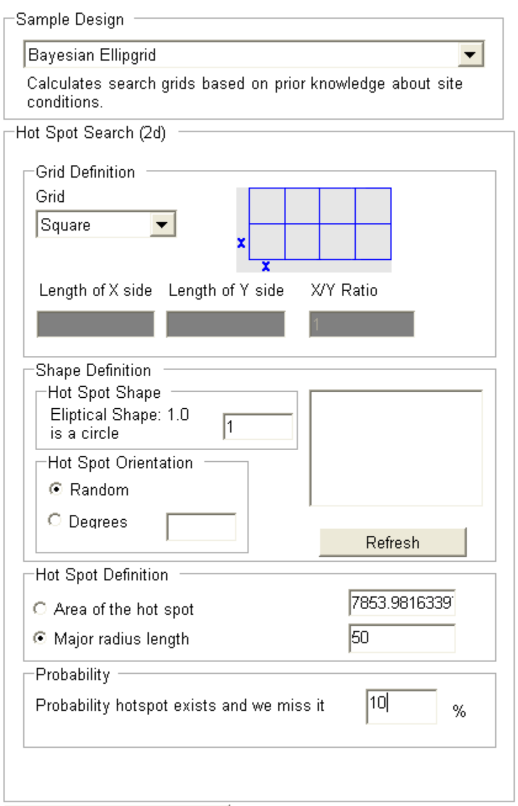

Figure 7-6 Input to SADA for the Example

Source: Stewart et al. 2009, p. 542

Suppose there is a circular elevated area with at least a 15-meter (50-foot) radius. The samples will be located on a square grid. Prior information is expressed in the map of the estimated probability that an elevated area exists in various locations on the site. Figure 7-5 indicates that three broad areas are estimated to be on the site where the likelihood of an elevated area is low (10 percent—purple), medium (50-50—green), and high (90 percent—red). The desired probability that an elevated area *does* exist and the grid has missed it should be no more than 10 percent. Such a map need not be overly detailed. It is used merely to put more samples where an elevated area is likely and fewer where it is not. This can be considered a semiquantitative expression of the same kind that is used in survey unit classification in MARSSIM.

Figure 7-7 shows that SADA places 37 new samples in accordance with the spatially delineated probability that the elevated area exists at all.

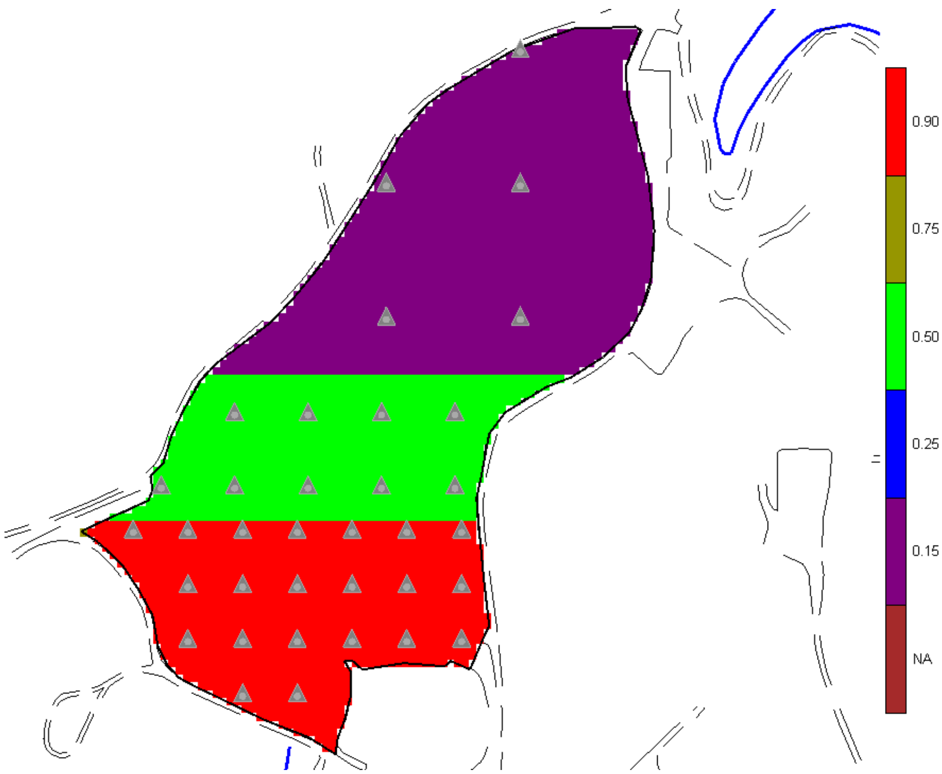

Figure 7-7 SADA Places 37 New Samples Based on the User-Defined Probability that the Elevated Area Exists

Source: Stewart et al. 2009, p. 543

This set of samples taken together produces a 10-percent chance that the hot spot does exist and is missed by sampling. In the northern part of the site, there is only a 15-percent chance that it exists at all. With a 10-percent limit, at least a few samples are needed. In the southern part of the site, more samples are worth taking. In fact, the closer the probability of existence is to 1, the closer the sampling design is to a traditional Ellipgrid model. The traditional non-Bayesian Ellipgrid, with no prior knowledge about a hot spot, requires 87 samples (shown in Figure 7-8) to search for a hot spot of the same size with a 90-percent probability of discovery. There is a 57-percent reduction in sampling requirements gained strictly by applying some prior knowledge about the site.

It is important to note that in SADA the user model can be defined in three dimensions. Chapter 33 of the SADA user's manual describes how to do this.

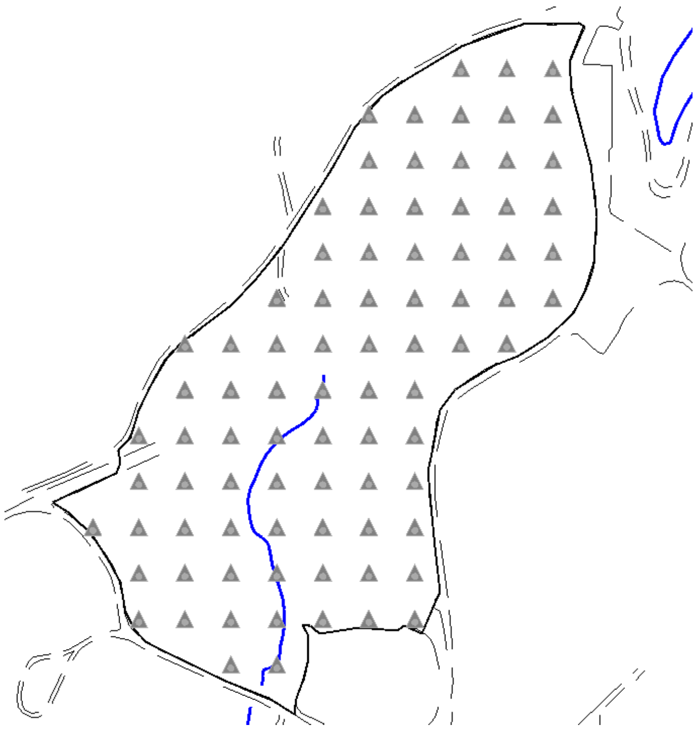

Figure 7-8 87 Samples Located To Search for a 50-Foot Circular Hot Spot with a 90-Percent Probability of Discovery and No Prior Knowledge of the Probability of Contamination

Source: Stewart et al. 2009, p. 544

The Bayesian Ellipgrid example above is from the SADA user's guide (pages 539 and following) (Stewart et al. 2009). The file Bayesian Ellipgrid.sda is included with the SADA Version 5 distribution and is installed along with the program.

7.4 CONSIDERATIONS IN SURVEY DESIGN

MARSSIM FSS designs are largely based on probability designs that specify the number of samples necessary to achieve the desired Type I and Type II error rates for a statistical hypothesis test. These samples are distributed either on a random start systematic grid for Class 1 and Class 2 survey units and random sampling across a Class 3 survey unit. These may not be the most efficient survey designs for SSUs. Section 8 covers some considerations for the FSS that may be more suitable for the subsurface. However, as noted above, the design and results of scoping and characterization surveys can be used to help design the subsurface FSS for an SSU. Given that (1) there may be prior data collected during the HSA and (2) the likelihood of finding subsurface residual radioactivity from the HSA will have been used to make preliminary SSU classifications, one can interpret this to mean that any design of a subsequent survey will in essence be a *secondary* sample design. Both VSP and SADA have the ability to use HSA data to aid in these secondary designs. The SADA user's guide, Part VII, Chapters 37–41 (Stewart et al. 2009), covers survey designs of several types and the VSP user's guide, Chapter 3 (Matzke et al. 2014), covers sampling plan development within VSP. Appendix E gives the table of contents for these guides.

After examining the available tools, the most promising methods for designing efficient subsurface surveys appear to be Bayesian Ellipgrid (geometrical) and Markov-Bayes (geostatistical). Section 8 will discuss this further.

8 GEOSPATIAL AND STATISTICAL METHODS

KEY POINTS

- The geostatistical tools in both SADA and VSP are based on the FORTRAN code in GSLIB (Deutsch and Journel 1998). VSP has recompiled the GSLIB code, and a dll was used to integrate it with VSP.
- VSP supports more classical statistical methods than SADA.
- SADA supports more geostatistical methods than VSP.
- Guidance is needed to define a subsurface survey unit (SSU) or subsurface volume.

In reviewing available geostatistical software for subsurface FSSs in Section 7 of this report, the recommendations were narrowed to SADA and VSP. Appendix E to this white paper lists the survey designs in VSP and SADA. Table 8-1 compares the features of these programs.

Table 8-1 Comparison of SADA and VSP Features

Software (Developer)	Cost	Dimensionality	Directed Workflow	Exploratory Data Analysis	Sample Design / Optimization	Structural Analysis	Anisotropic Variograms	Point Kriging	Block Kriging	Universal Kriging	Co-Kriging	Indicator Kriging	Spatial-Temporal Krgiing	Discontinuities / Complex Geometries	Conditional Simulation	Cross-Validation	Fate and Transport Modeling	Dose Assessment	Geographical Information System	Highlights
VSP (Pacific Northwest NL)	Free	2D	●	●	●	●		●	●			●	●						[1]	Walsh's outlier test, data quality objective (DQO) base sampling, ecoomic analysis.
SADA (University of Tennessee)	Free	3D	●	●	●	●	●	●			●	●			●	●		●[2]	●	Area of concern maps, math arithmetic, sampling optimization, remediation cost-benefit analysis

[1] If a map of the site in .DXF or .SHP format has been saved in the VSP folder, it can be imported into the VSP project.
[2] SADA performs only ecological dose assessment.
Source: McGrath et al. 2017

8.1 THE DATA QUALITY OBJECTIVE PROCESS

This section discusses the use of geospatial and statistical methods to evaluate remediated sites and the design and analysis of FSSs, especially allowing comparison to regulatory release criteria. The section also examines the applicability of MARSSIM statistical tests and possible alternative methods as appropriate. This includes the issue of analysis software that might be used to support a release decision for an SSU. This involves the DQO process and limiting decision error rates.

Step 1. Problem Statement

Determine if there is residual radioactivity in an SSU that exceeds release criteria radioactivity.

Part of the problem statement would be a CSM and a contaminant concern map (CCM) (see NUREG/CR-7021 (Stewart 2012)). The initial version of the model and map, which would be prepared early in the decommissioning process and evolve as more data are obtained, should delineate the boundary of the site's impacted areas. The CCM should be used to aid the formation and classification of survey units (Class 1, 2, and 3). MARSSIM and MARSAME contain specific guidance on the size of survey units and the degree to which residual radioactivity is believed to exist in a particular class. The survey unit class determines the type and intensity of the FSS required. Definition of the SSU classes should be considered early in the development of SSU guidance. It may be advantageous to obtain cores in surface survey units at the same time that surface samples are taken, even if the boundaries of surface and SSUs may not align. Not every section of the core needs to be analyzed for residual radioactivity but all sections should be kept until the license is terminated in case further information is required. The depth and segmentation of the cores should be determined using the CCM and HSA as a guide. If there is sufficient sensitivity, the entire core can be scanned. Compositing samples from different levels may also be appropriate to control analytical costs.

Step 2. Identify the Decision

Determine whether the SSU requires further remediation, or the material must be treated, or disposed of, as radioactive, or if the survey unit can be released.

The goal of this step is to define the questions that the study will attempt to resolve. For example, study questions might include "Are contaminants present in soil and sediment at the site that exceed appropriate release criteria?" and "What is the volume of soil that requires offsite disposal?" Decision statements are then developed, and multiple decisions are organized into a decision logic diagram, in which each branch terminates in an action statement or set of actions that must be undertaken to resolve the problem (ANS 2008).

For subsurface soils, guidance is not yet available to develop decision statements.

Step 3. Identify Inputs to the Decision (the DCGLs)

What average level of residual radioactivity concentration in the SSU is unacceptable (i.e., the $DCGL_W$), and what concentration above this would define an elevated area (i.e., the $DCGL_{EMC}$)?

This is meant to establish the action level for the decision rule. The analyst should use the final version of NUREG-1757, Volume 2, Revision 2, Appendix G, Section G.3, on surveys for special situations on land (NRC 2020c). Section 3 of this letter report discusses DCGLs.

Step 4. Define the Study Boundaries

Identify the location and extent of the SSU, the classification of the SSU, the available instrumentation and analysis, the number of samples needed, where the samples should be taken, how they should be taken, and the resources available for the measurements.

In this step, spatial, temporal, and practical boundaries to the problem are set. This helps narrow the problem (ANS 2008). The analyst should determine whether geophysical measurements are needed to aid in locating areas where subsurface residual radioactivity would occur, presumably during the scoping and characterization processes. For the FSS, these measurements may be needed as a final check that something was not missed.

Appendix A to ISO Standard EN ISO 18557:2020 refers to the number of samples that may be needed to fit a variogram. In that case, the distance between points is important. ISO defaults to taking 200 data points per hectare (corresponding to a 7-m grid size) for contaminated soils around nuclear facilities, while allowing a grid range from 5 to 10 m depending on results of the HSA (ISO 2020).

Guidance is needed to define an SSU and a subsurface volume. Will there be classes of subsurface soils? Will there be averaging rules for volume contamination and over how large of a volume the contamination may be averaged for compliance?

Step 5. Develop a Decision Rule

Develop a rule so that when the samples are collected, appropriate measurement data are obtained, and the analyst can determine the disposition of the SSU.

The decision rule usually involves computing a statistic from the data and comparing that result to a predetermined number (i.e., the critical level). Whether the value is greater or less than the critical level, the decision is made. The statistic can be a number evaluated for each sample or can be an aggregate of a subset of the data, such as a mean, or a CCM of the SSU. Appendix F to this white paper lists the survey designs in VSP and SADA. The decision rule is framed in terms of a statistical hypothesis test.

Tests Available from MARSSIM

In addition to the WRS and Sign tests, MARSSIM recommends a wide variety of statistical tests designed for use in specific situations. MARSSIM Table 2-3 lists several examples of alternative statistical tests that are recommended by MARSSIM for use at individual sites or survey units. The table also contains a brief description of the alternative recommended tests, the probability model assumed, the type of test, references, and advantages and disadvantages of obtaining additional information on these tests. A statistician may be required (MARSSIM, draft Revision 2 (NRC 2020b)).

Appendix F to this white paper presents a listing and description of alternative MARSSIM-suggested tests.

Decision Rules as Sampling Goals in VSP

The table below is from Section 3.1.1 of the VSP user's guide (Matzke et al. 2014), edited to show the sampling plans most relevant for subsurface survey designs. If the MARSSIM version of VSP is loaded, only MARSSIM survey designs are shown, and the input parameter dialog references MARSSIM terminology. The phrase "*Calculate number of samples*" in Table 8-2 is italicized to emphasize that VSP computes the number of samples needed for most of its methods, based on parameters entered by the user.

In this table, the term "proportion" refers to the percentage of values that meet a certain criterion or fall into a certain class. The action level (AL) is then stated as a value from 0.01 to 0.99.

Table 8-2 VSP Sampling Problems To Be Resolved

Sampling	Description[1]
Compare Average to Fixed Threshold (MARSSIM)	*Calculate number of samples* needed to compare a sample mean or median against a predetermined threshold and place them on the map. This is called a one-sample problem.
Compare Average to Reference Average (MARSSIM)	*Calculate number of samples* needed to compare a sample mean or median against a reference mean or median and place them on the map. This is typically used when a reference area has been selected (i.e., a background area) and the problem is to see if the study area is equal to, or greater than, the reference area. This is called a two-sample problem because the data from two sites are compared to each other.
Estimate the Mean	*Calculate number of samples* needed to estimate the population mean and place them on the map.
Construct Confidence Interval on Mean	*Calculate number of samples needed* to find a confidence interval on a mean and place them on the map.
Locate Hot Spots	Use systematic or approximate grid sampling or multiple increment sampling to locate a hot spot (i.e., small pockets of contamination).
Show that at least some high percentage of the sampling area is acceptable	*Calculate number of samples* needed to confidently show that little if any contamination is present or exceeds a specified threshold.
Discover Unacceptable Areas with High Confidence	Develop sampling designs to discover, with high probability, contaminated areas (unacceptable grid cells) if they exist.
Combined Average and Individual Measurement	Compare the results of two designs, to see which one requires the most samples to meet its sampling goals.
Add Sampling Locations To Reduce Spatial Uncertainty (Kriging)	Place additional samples to improve estimates based on a geostatistical analysis of existing data.
Compare Proportion to Fixed Threshold	*Calculate number of samples* needed to compare a proportion to a given proportion and place them on the map.
Compare Proportion to Reference Proportion	*Calculate number of samples* needed to compare two proportions and place them on the map.
Construct Confidence Interval on Proportion	*Calculate number of samples* needed to find a confidence interval on a proportion and place them on the map.
Estimate the Proportion	*Calculate number of samples* needed to estimate the population proportion and place them on the map.
Establish Boundary of Contamination	Determine whether contamination has migrated across the boundary.
Radiological Transect Surveying	Calculate transect survey spacing required to traverse and detect a radiological hot area. Evaluate postsurvey hot spot detection and mapping.

[1] In a number of places in Table 8-2, the text is italicized to emphasize that VSP computes the number of samples needed for most of its methods, based on parameters entered by the user.

Source: Matzke et al. 2014, Section 3.1.1

VSP has an "Expert Mentor," which can help guide the user through the sampling planning process:

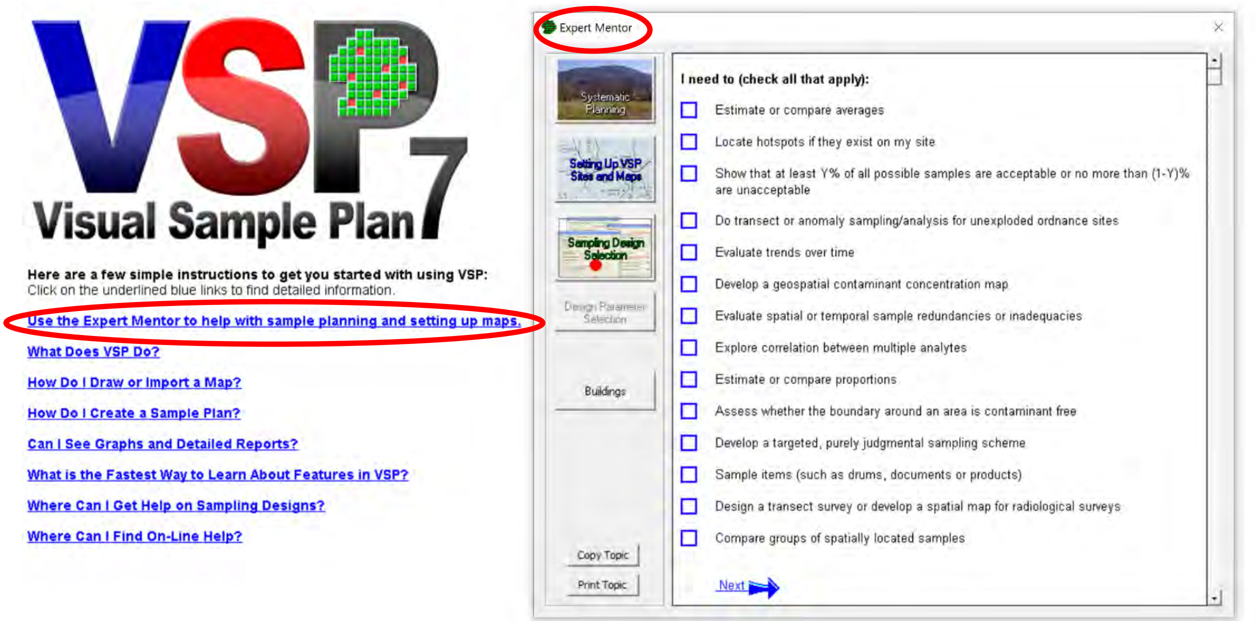

Figure 8-1 VSP Expert Mentor Screen

Source: VSP Version 7.15

In the VSP top control ribbon, select "Sampling Goals." Many of the options under "Sampling Goals" have either parametric or nonparametric choices. Stratified, Ranked set, and Collaborative sampling are found under "Estimate the Mean," all of which are under "Data not required to be normally distributed," as shown in Figure 8-2 below.

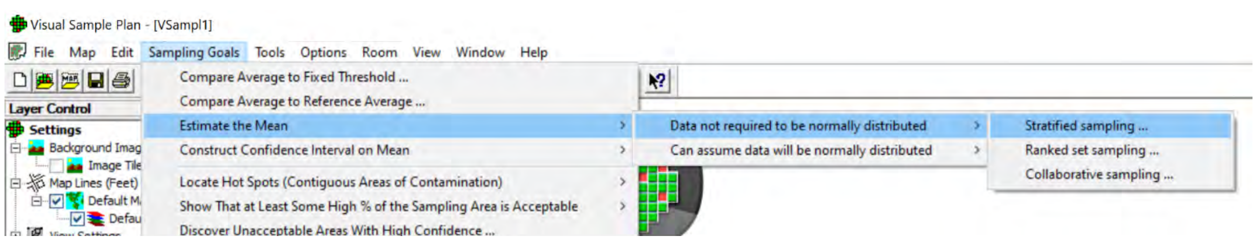

Figure 8-2 VSP Sampling Goals Screen

Source: VSP Version 7.15

Composite sampling is found under “presence/absence” sampling, as shown in Figure 8-3. Composite sampling is also an option under VSP sampling goals that implement MARSSIM sample designs such as “Compare Average to Fixed Threshold” and “Compare Average to Reference Average.”

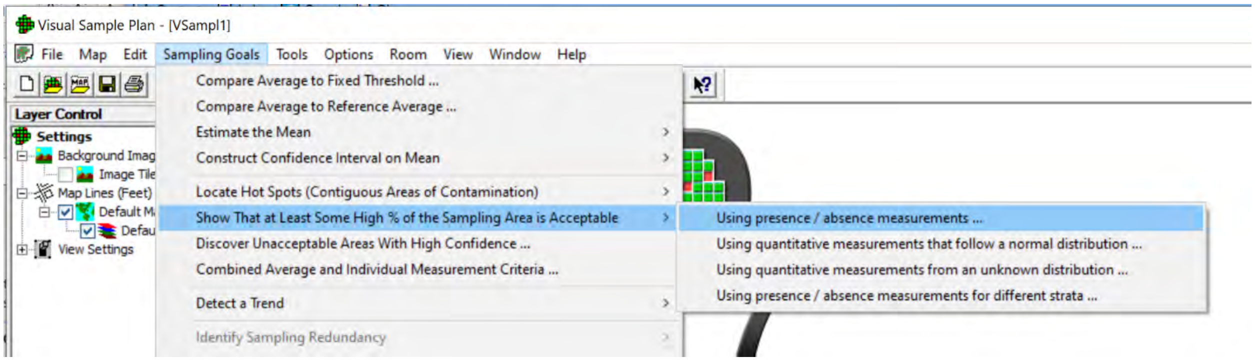

Figure 8-3 VSP Selection of Presence/Absence Measurements Screen

Source: VSP Version 7.15

As shown in Figure 8-4 for this example, change the confidence levels to “99.000%” confident that at least “95.000%” of all the grid cells are acceptable. Also change the number of grid cells in the survey area to 1000. Note that prior information about the number of cells that are acceptable can be used, giving the sample placement a Bayesian flavor.

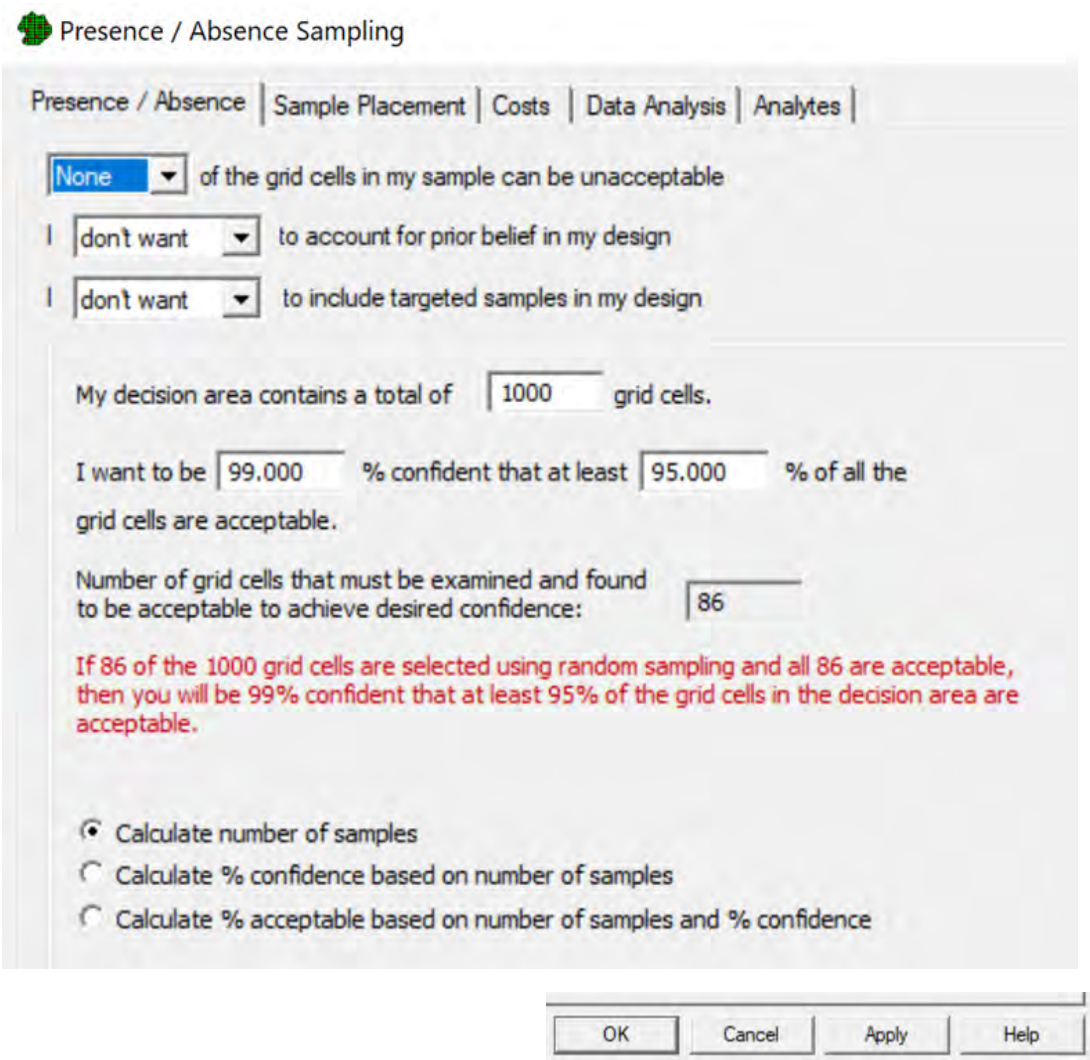

Figure 8-4 VSP Presence/Absence Measurements Screen

Source: VSP Version 7.15

Select the “sample placement” tab, as shown in Figure 8-5.

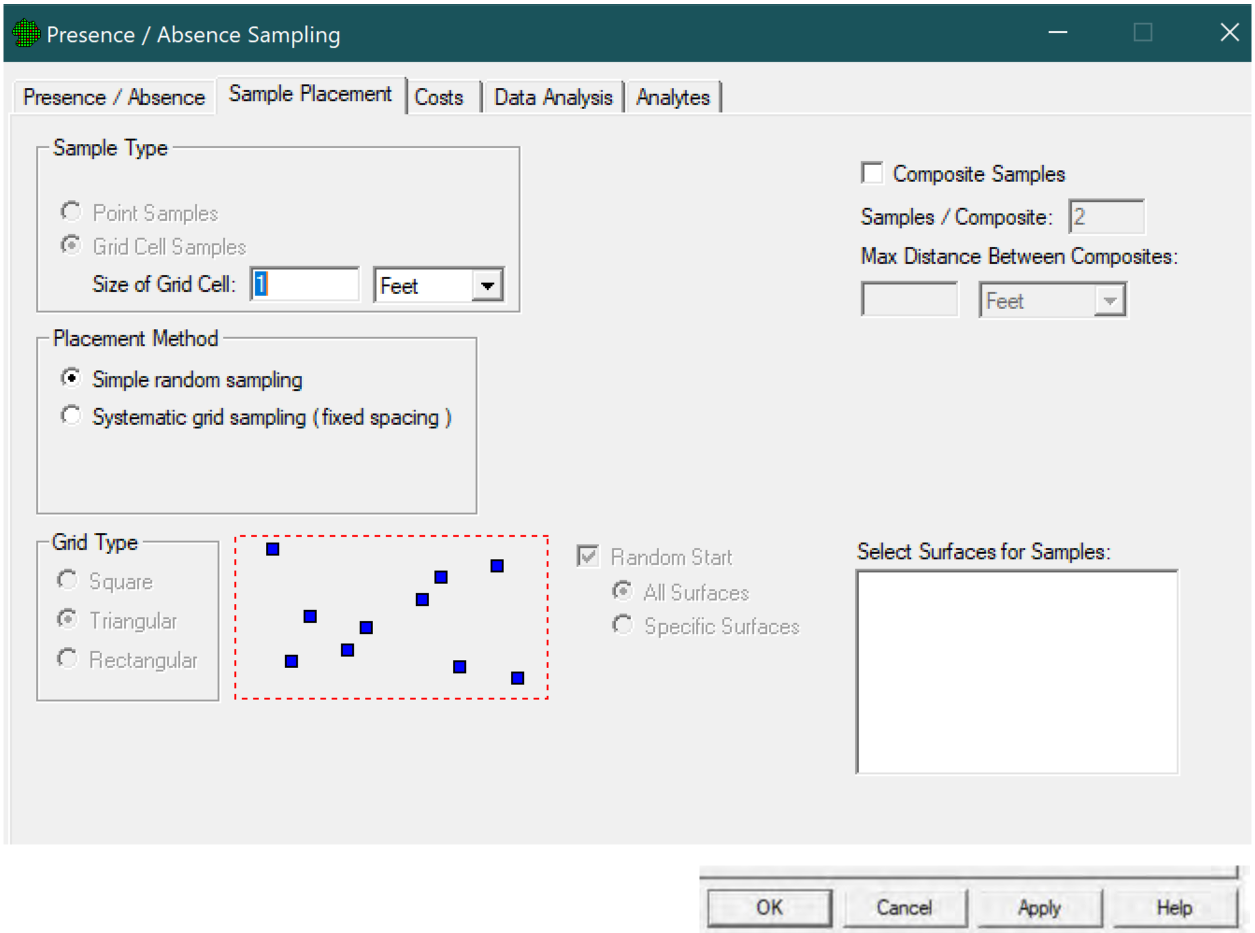

Figure 8-5 VSP Sample Placement Screen

Source: VSP Version 7.15

To find a hot spot using the method of Ellipgrid, select the “Sampling Goals” tab and “Locate Hot Spots Contiguous Areas of Contamination” and “Assume no false negative errors,” as shown in Figure 8-6.

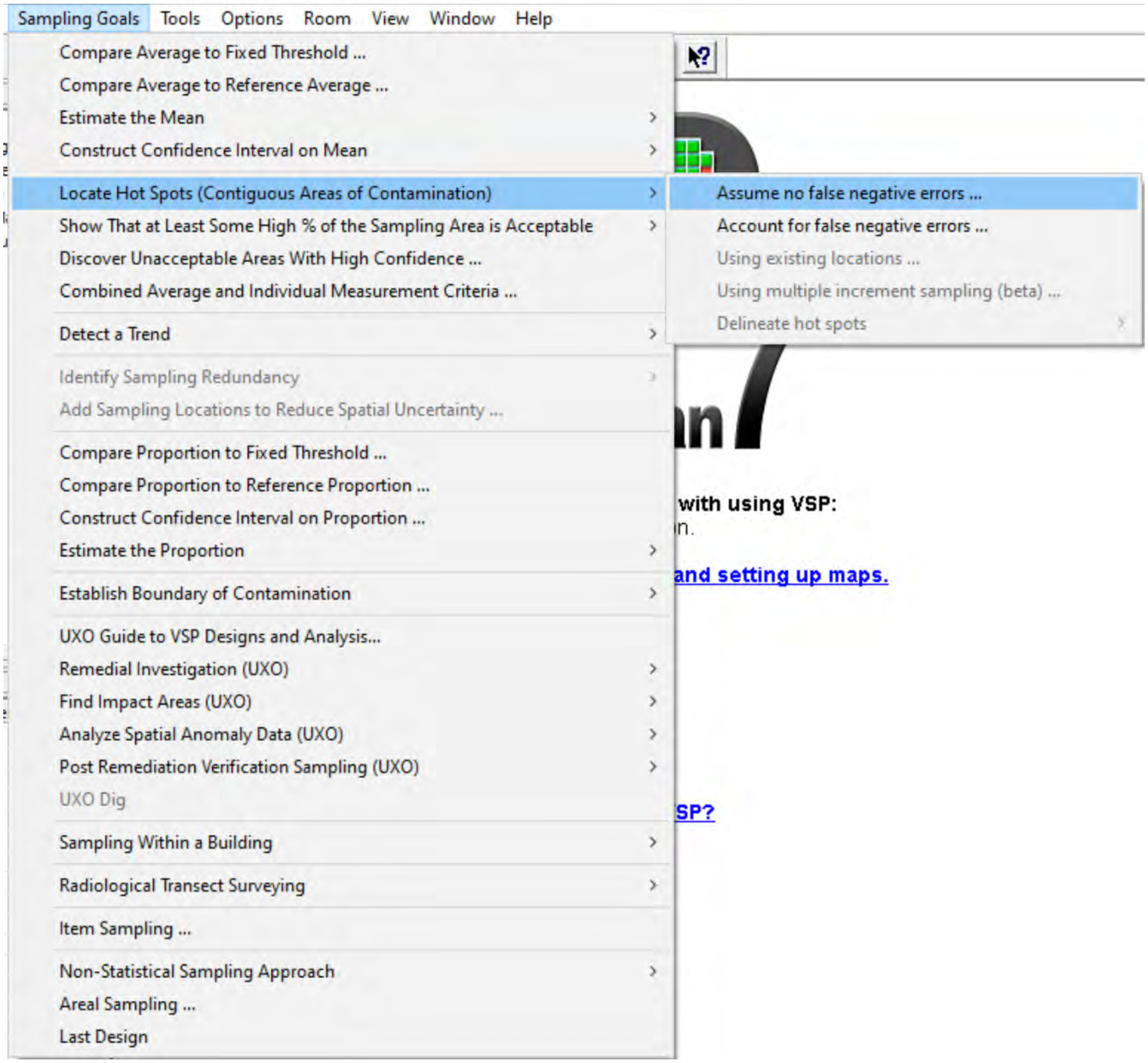

Figure 8-6 VSP Sampling Goals Screen for Locating a Hot Spot

Source: VSP Version 7.15

VSP identifies locations on the surface, so information about the depth of cores and the sampling increment must be specified separately. Current guidance in NUREG-1757, Volume 2, Appendix G, suggests not exceeding 1 m in depth. It is not acceptable to average radionuclide concentrations over an arbitrary soil thickness.

Geostatistical (kriging) maps can be produced under the “Add Sampling Locations to Reduce Spatial Uncertainty” in the “Sampling Goals” tab. However, most of the geostatistical tools are contained in the UXO module of VSP.

Decision Rules in SADA

NUREG/CR-7021 addresses a subsurface decision model for supporting environmental compliance decisions in SADA (Stewart 2012). SADA contains the procedures for a wide range of geostatistical analyses of data. Classical statistics generally assume that the data are independent and identically distributed. Geostatistical methods can estimate a probability distribution as a function of location, allow the spatial relationship among nearby data points to be taken into account, and produce an estimate of uncertainty associated with the predicted values.

NUREG/CR-7021 provides a geospatial modeling and decision framework for conducting a subsurface compliance survey and analysis for sites that have been remediated for radioactive contamination (Stewart 2012). In the SADA user's guide (Stewart et al. 2009), Chapters 28, 30, and 31 cover basic and advanced geospatial methods. Chapter 31 contains practical cookbook recipes for ordinary kriging, indicator kriging and co-kriging. Kriging is an exact interpolator that predicts a value that is identical to the measured value at a sampled location. Interpolation predicts values that fall within the range of data values. Extrapolation predicts values for points outside the range of data values. The kriging value at an unsampled point is a weighted average of nearby data. Because it is an interpolator, the kriged estimate cannot exceed the largest sample observed. SADA can perform indicator kriging to estimate the probability that the $DCGL_W$ is exceeded at a point.

Bayesian Ellipgrid can be used to summarize prior knowledge of residual radioactivity in terms of the belief that there may be elevated areas on the site. Chapter 40 of the SADA user's guide (Stewart et al. 2014) and Section 7 of this white paper discuss this technique. The number of samples is based on what are called "user models." (See Chapter 33 of the SADA user's guide for a description of the user models.)

Once these data (hard data) are collected at the locations specified by Bayesian Ellipgrid, a secondary sampling plan can be designed using Markov-Bayes. Markov-Bayes is a special application of the Markov model to a map of local prior probabilities (soft data). Rather than ordinary co-kriging, an indicator co-kriging approach is used, whereby hard data are first converted to zeros or ones, depending on whether they exceed a specified criterion. The co-kriging method is then applied to these zeros and ones along with the prior probability map. This results in an updated probability map that reflects the influences of both the hard and soft data. In SADA, one must first create a prior probability map. (This is done by creating a user-defined map and then choosing the interview "Update My Probability Map.") SADA can apply Markov-Bayes only to user-created models. Chapter 30 of the SADA user's guide (Stewart et al. 2009) and Section 7 of this white paper give an example.

Chapter 9 of NUREG/CR-7021 examines compliance surveys. These are called final status surveys (FSSs) in MARSSIM, and the following discussion follows this convention. The compliance decision under NUREG/CR-7021 has three elements:

(1) a prior CCM that is the best available representation of site contamination at the time the FSS is planned

(2) the data values from the FSS

(3) the updated CCM based on the prior CCM and the FSS (can be called the final CCM)

NUREG/CR-7021 classifies the decision scale as follows:

- local (the value at a location)
- areal (the average over a survey unit)
- global (the sitewide average)

The value at a location can be (1) the measured value or (2) the predicted SADA value.

The predicted value may be a high (e.g., 90th or 95th) upper percentile of the SADA modeled distribution of data at each point.

One possible decision rule would be that the survey unit passes if it meets both of the following criteria:

(1) Every measured data point is below the $DCGL_V$.
(2) Every predicted value is below the $DCGL_{EMC}$.

The $DCGL_{EMC}$ would be a limit on an upper percentile of the SADA-predicted distribution.

When a comparison to a limit is based on a predicted distribution, it is referred to as "stochastic"; otherwise, it is referred to as "deterministic."

NUREG/CR-7021 suggest another procedure, called "Check and Cover." In terms of FSS design, use of p-median and check and cover is an interesting option, but it is unproven. (When MARSSIM was being developed, three proof-of-concept surveys were done at real facilities.) Check and cover does not establish the number of samples needed to achieve desired Type I and Type II error rates for a hypothesis test. Bayesian Ellipgrid would appear to come close to this, followed by a Markov-Bayes secondary sampling design. The number of sample cores needed might initially be limited to the number that would be required for the Sign or WRS test if the survey unit were on the surface. If the survey unit passes the median (Sign or WRS) test for the grid cores, and the stochastic test for the $DCGL_{EMC}$, that may be enough to be fairly sure that the survey unit has been adequately remediated. Alternatively, the probability of detecting an elevated area using Bayesian Ellipgrid could be used in the survey design to estimate a Type I error rate for the survey sample design. This would link the number of samples to a probability of decision errors more like that in MARSSIM.

Step 6. Specify Limits on Decision Errors

State the acceptable error tolerances.

Four outcomes are possible when applying a decision rule to construct a final CCM:

(1) The survey unit does not meet the release criterion, and after computing the test statistic and comparing it to the critical value, analysts decide that it does not meet the release criterion. This is the correct decision.

(2) The survey unit does meet the release criterion, and after computing the test statistic and comparing it to the critical value, analysts decide that it does meet the release criterion. This is the correct decision.

(3) The survey unit does not meet the release criterion, and after computing the test statistic and comparing it to the critical value, analysts decide that it does meet the release criterion. This would be a decision error.

(4) The survey unit does meet the release criterion, and after computing the test statistic and comparing it to the critical value, analysts decide that it does not meet the release criterion. This would be a decision error.

MARSSIM Sections 2.5, 5.3.1, and D.1.6 discuss hypothesis tests. To determine whether Scenario A or Scenario B will be used to evaluate the survey unit, consider the following:

- Scenario A uses a null hypothesis that assumes the concentration of radioactive material in the survey unit exceeds the $DCGL_V$. Scenario A is sometimes referred to as "presumed not to comply" or "presumed not clean."

- Scenario B 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" (MARSSIM Section 5.3.1).

State the null hypothesis (H_0):

- For Scenario A, the concentration of residual radioactive material in the survey unit exceeds the release criteria (Section 2.5, Appendix D, Section D.1.6).

- For Scenario B, the residual radioactive material in the survey unit does not exceed the release criteria (Section 2.5, Appendix D, Section D.1.6).

The example decision rule discussed in Step 5 might be used as Scenario A for a Class 2 SSU. Following MARSSIM terminology, Class 2 areas would be those that have, or had before remediation, a potential for residual radioactive material or known residual radioactive material but are not expected to exceed the $DCGL_V$. Here the $DCGL_{EMC}$ would be a limit on the upper percentile of the SADA-predicted distribution, say 90 percent. This is a novel application of the concept of a $DCGL_{EMC}$. A decision error analogous to a Type I error rate might be defined as 1.0 – 0.9 = 0.1 or a 10-percent chance that the concentration of radioactive material in the survey unit exceeds the $DCGL_{90\%}$. Clearly, much more consideration of decision rules such as those promulgated in NUREG/CR-7021 and the corresponding decision error rates would be needed.

The easiest way to learn how to do specific tasks in SADA is to open the program and choose "Help" from the menu, as shown in Figure 8-7.

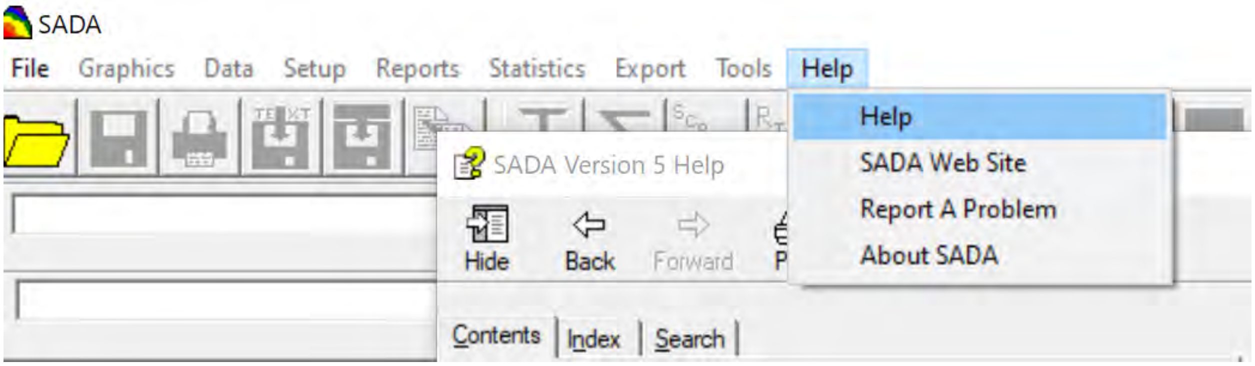

Figure 8-7 SADA Help Menu

Source: SADA Version 5.0

As shown in Figures 8-8 and 8-9, SADA uses an “interview” metaphor to prompt the user for the data and parameters it needs to perform the desired analysis.

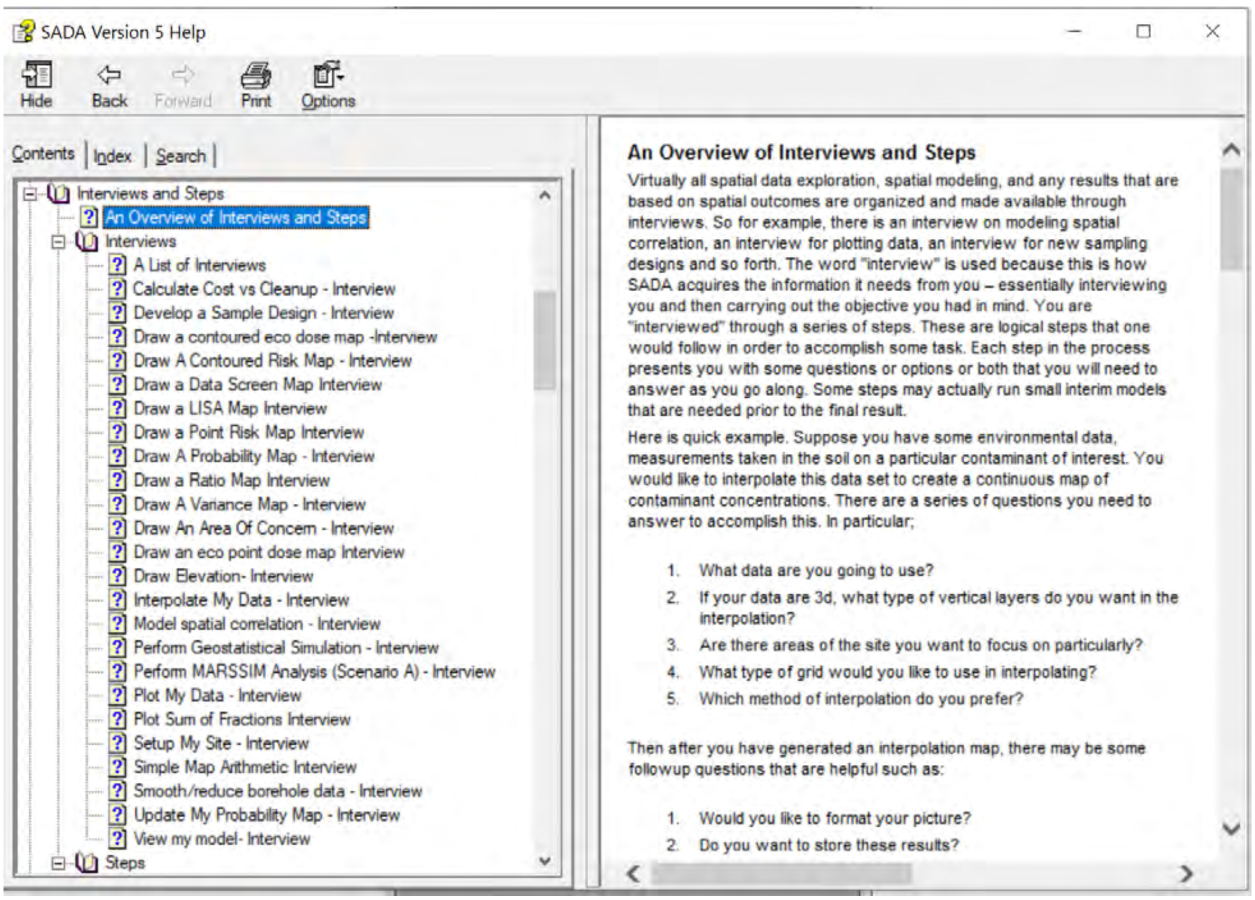

Figure 8-8 SADA Interview Help Menu

Source: SADA Version 5.0

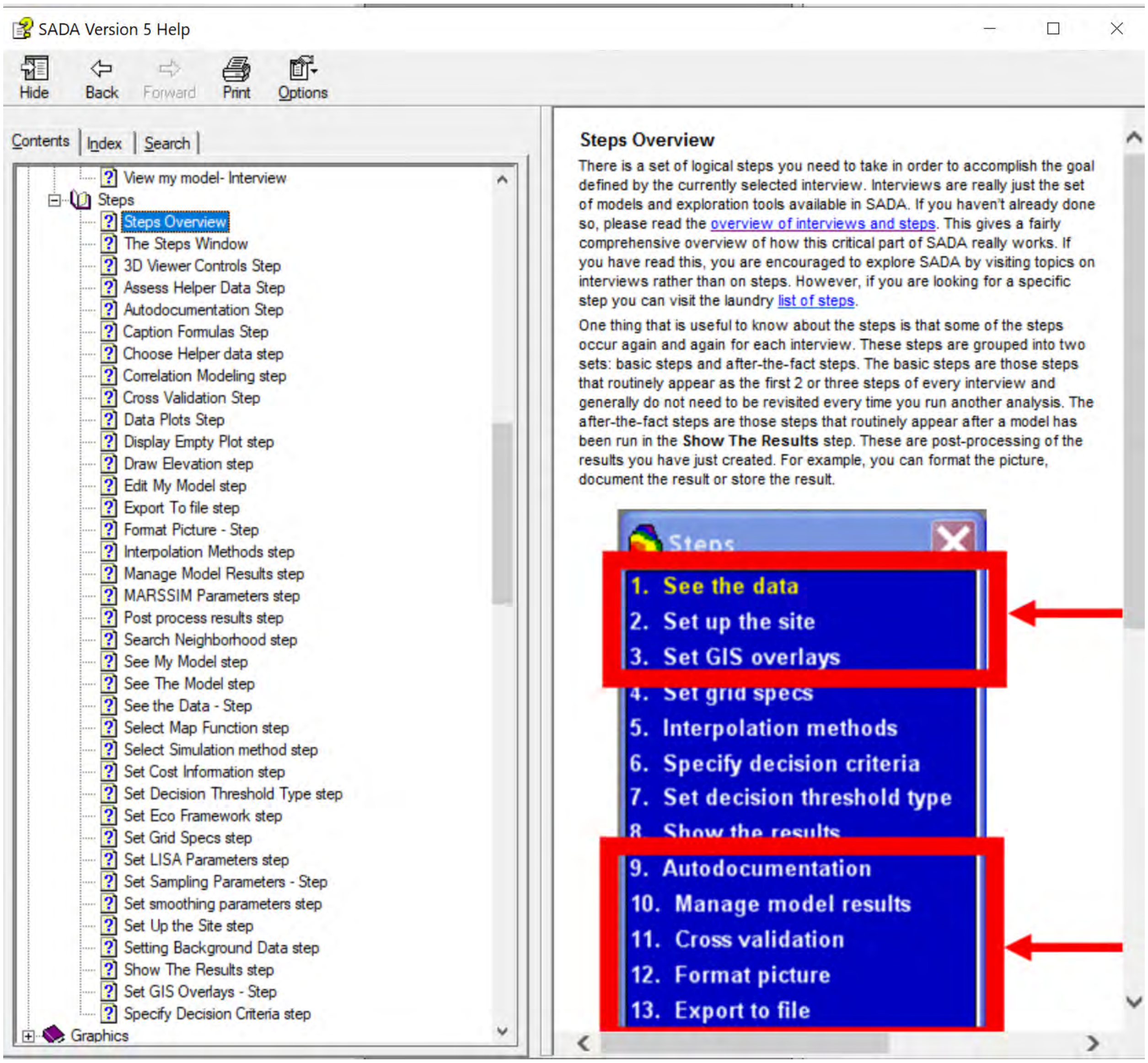

Figure 8-9 SADA Interview Step Menu

Source: SADA Version 5.0

From the "Contents" menu, choose "Sample Designs" as shown in Figure 8-10. This will show a list of the available sample designs.

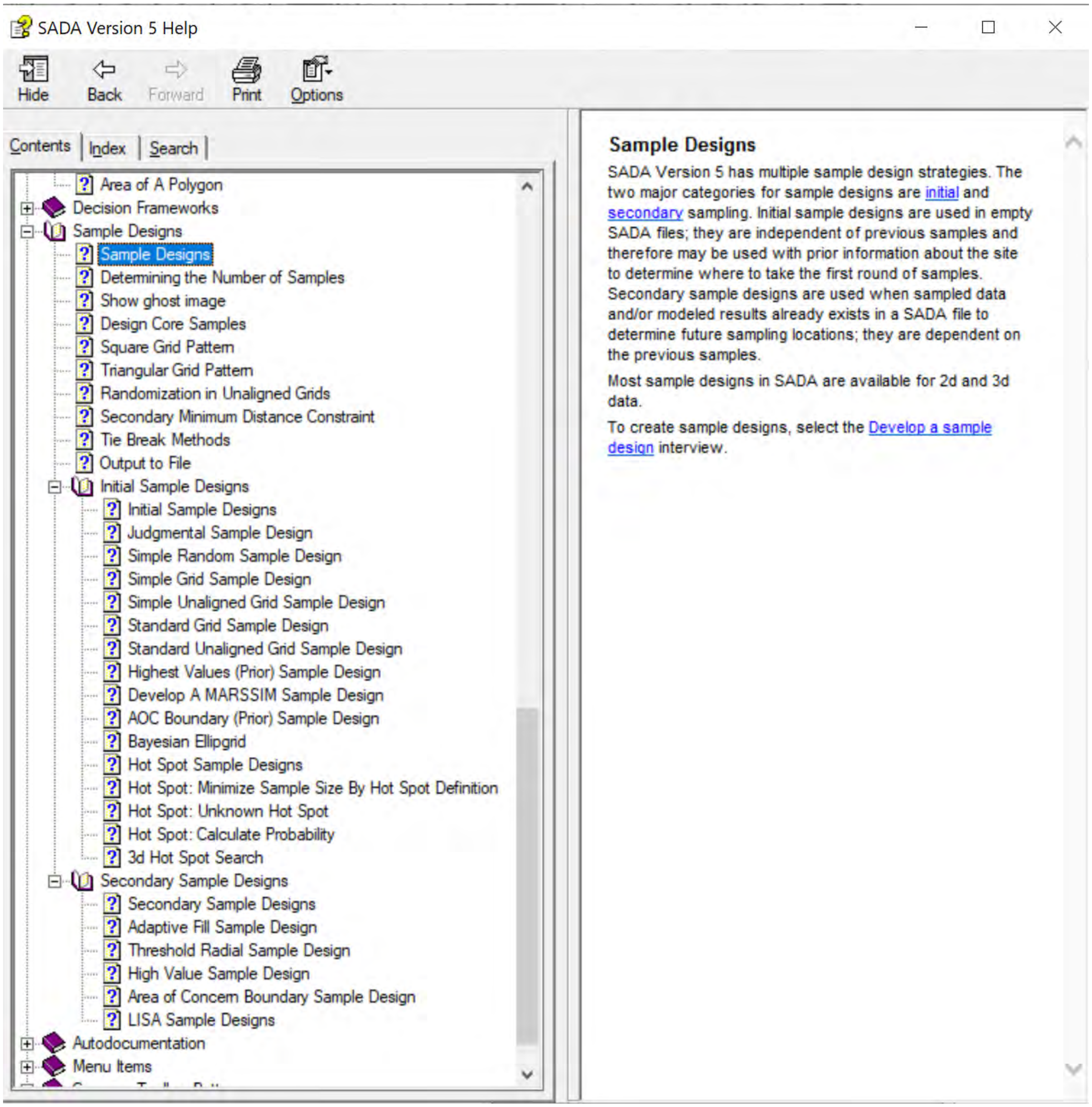

Figure 8-10 SADA Sample Design Help Menu

Source: SADA Version 5.0

Simarily, as shown in Figure 8-11, from the “Contents” menu, choose “Geospatial Methods,” which will show a list of the available methods.

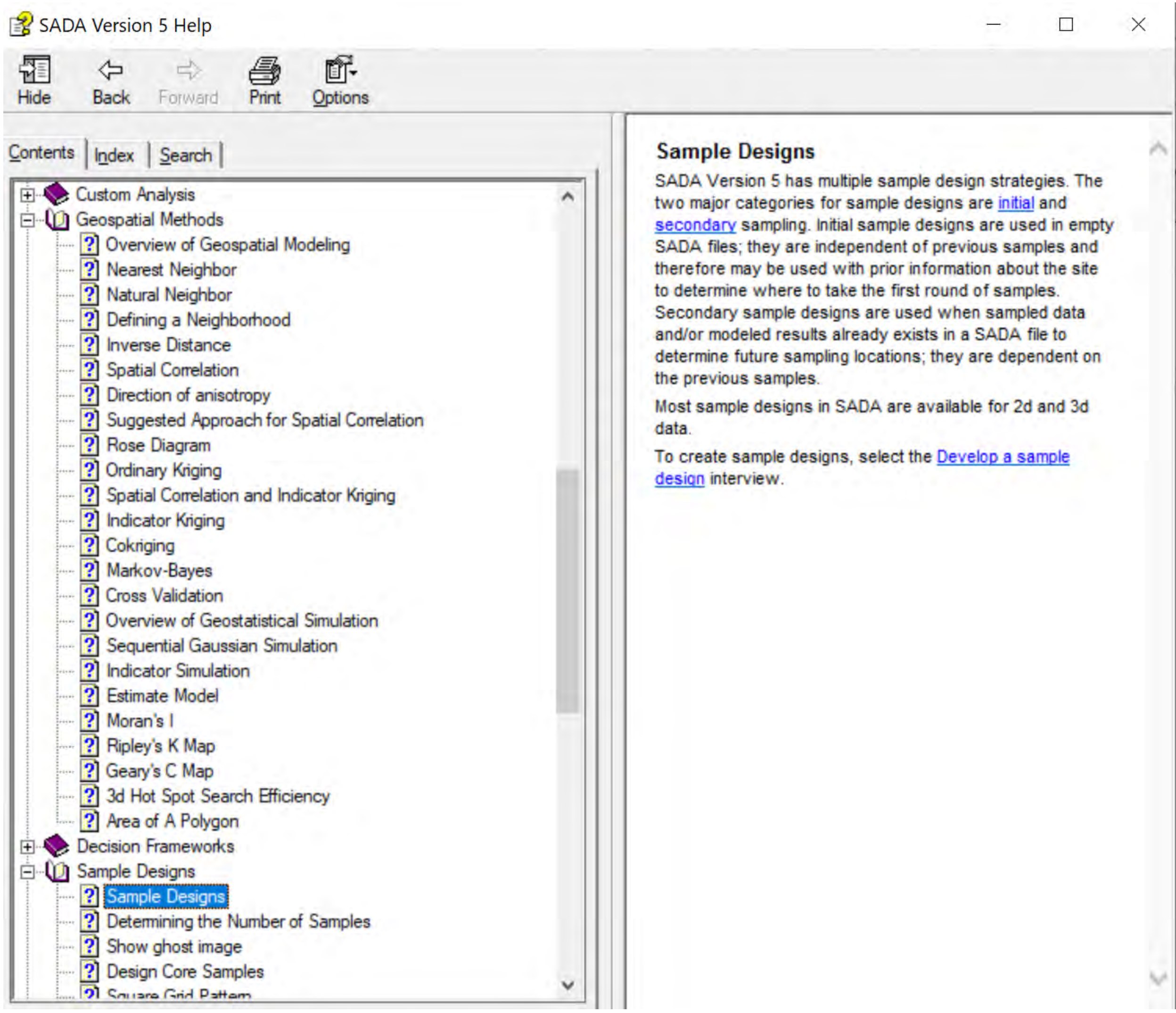

Figure 8-11 SADA Geospatial Methods Help Menu

Source: SADA Version 5.0

As shown in Figure 8.12, selecting “Statistics” will present the statistical summaries and tests available.

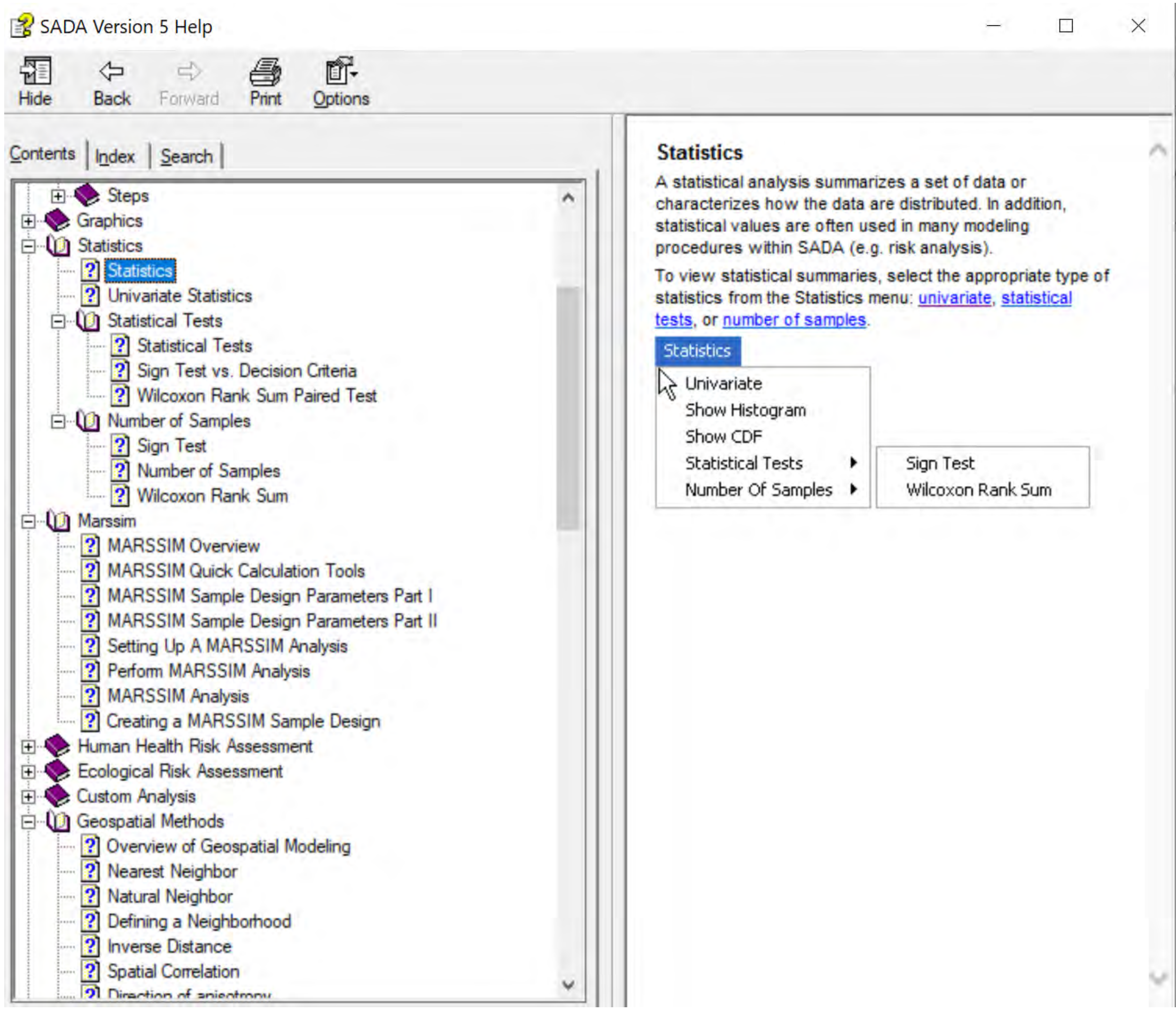

Figure 8-12 SADA Statistical Summaries and Tests

Source: SADA Version 5.0

Step 7. Optimize the Design for Obtaining the Data

Choose a sampling design that meets the DQO requirements.

Once all the inputs are provided, a team knowledgeable in statistical sampling designs and statistical tests can use all the information from Steps 1 through 6 to devise a sampling design. This design specifies the number of samples, location and timing of samples, type of samples, type of measurement and collection equipment, and scanning versus sampling, among other factors (ANS 2008).

8.2 SUMMARY

Appendix G.3 to NUREG-1757, Volume 2, Revision 2, discusses current methods for conducting surveys for special situations on land. Although MARSSIM does not apply to subsurface soils, a MARSSIM-based approach may be extended to subsurface problems. Presumably, the characterization surveys have delineated the depth of the residual radioactivity. In many cases, a layered approach has been used in which multiple subsurface layers or strata are considered individually and then the cumulative risk from the multiple layers or strata is assessed. As each layer is exposed or remediated, a MARSSIM survey is performed for the surface soil, often defined as the top 15 cm. This is a rather cumbersome and inefficient method. Other approaches to characterizing the distribution of subsurface contaminants could involve taking many cores, which could be scanned or subsampled or optimized by some designs like the Check and Cover design described in NUREG/CR-7021.

Obtaining the number of measurements for the EMC is often impractical. HTD radionuclides are typically those that emit alpha or beta particles, but no, or difficult to measure, gamma rays, making them hard to detect and quantify with scan measurements, especially in soil. Thus, during the DQO process, the analyst determines the acceptable risk, *p*, of not detecting an area of elevated concentrations of radioactive material. This risk can be estimated using Table I.5 in MARSSIM, draft Revision 2, Appendix I. This also requires estimate of the size of an area with an elevated concentration of residual radioactive material and the associated $DCGL_{EMC}$. As this size decreases, the risk of missing an elevated area increases. These considerations apply equally to subsurface residual radioactivity that cannot be detected on the surface. Several sampling plans in both VSP and SADA would also require that the risk of not detecting an elevated area of a given size be specified.

MARSSIM, draft Revision 2, Appendix E, provides an approach for augmenting FSSs involving HTD radionuclides in soil with ranked set sampling strategies. Another approach is composite sampling, which is discussed in NUREG-1505, Chapter 14.3 (NRC 1998a). NUREG-1757, Volume 2, Revision 2, contains guidance for the use of composite soil sampling for demonstrating compliance with radiological release criteria (NRC 2020c).

NUREG/CR-7021 presents a framework focused on development of a conceptual site model referred to as a CCM. The CCM describes the extent, location, and significance of residual radioactivity relative to the decision criteria. The CCM can be developed with the aid of visualization, GIS, and geostatistical software. Geostatistical methods often require complex input parameters and calculations to update a CCM. The assistance of an experienced geostatistician may be required in most cases. There are two software aids that can also help, VSP and SADA. VSP supports more classical statistical methods, and SADA supports more geostatistical methods. VSP is 2D and SADA is 3D. VSP supports ranked set and composite sampling. The ideal tool would have the classical and geostatistical methods of each software combined into a single software so that a broader choice of sampling plans would be available.

The geostatistical tools in both VSP and SADA are based on the FORTRAN code in GSLIB (Deutsch and Journel 1998). VSP has optimized the code by recompiling, and GSLIB has been ported to a more modern language, PYTHON (https://github.com/GeostatsGuy/GeostatsPy). Many geostatistical functions are available in the R packages, including the following:

- **gstat** (https://cran.r-project.org/web/packages/gstat/gstat.pdf)
- **georob** (https://cran.r-project.org/web/packages/georob/vignettes/georob_vignette.pdf)

9 ASSESSING BACKGROUND AND SCENARIO B

This section evaluates challenges associated with assessing background radionuclide concentrations and disaggregating background radioactivity from residual activity resulting from licensed activities. The applicability of Scenario B to subsurface residual radioactivity and practical approaches for demonstrating indistinguishability from background are discussed.

KEY POINTS

- Often, the cleanup criterion is very close to background, including doses from ground water.
- Scenario B is not yet implemented in SADA or other 3D software, and identification of software for this purpose remains a data gap. VSP does implement Scenario B.
- Appendix G to NUREG-1757, Volume 2, does contain examples of Scenario B for 3D data.
- MARSSIM, Revision 2 (draft), has been published for public comment. The manual discusses Scenario B in detail; however, more explanation is needed on to how to derive a discrimination limit (DL).

An understanding of what makes up background radiation is necessary to determine exceedance of the criterion of 25 mrem above background value. Often, the 25-mrem criterion is very close to background levels (including doses from ground water) and distinguishing between them can be difficult. Even the part of the country where the survey is being performed may be critical in the analysis, as background can vary dramatically. Appendix G to this white paper provides details on the natural background suite of radionuclides, including regulatory considerations, survey design considerations, and selection of background reference areas.

MARSAME (NRC 2009a) incorporates technical information from NUREG-1505, Revision 1 (NRC 1998a), and NUREG-1576, “Multi-Agency Radiological Laboratory Analytical Protocols Manual” (MARLAP), issued July 2004 (NRC 2004), for designing surveys using Scenario B. The assignment of values to the lower bound of the gray region (LBGR) and upper bound of the gray region (UBGR), specification of decision error rates, and classification are all similar to information in MARSSIM, Revision 1 (NRC 2000a).

NUREG-1757, Volume 2, states that Scenario B is used when the assumption is made that the mean concentrations of contaminants in the survey unit are indistinguishable from those in background. MARSSIM, draft Revision 2, states that the Scenario B null hypothesis is that the concentration of residual radioactive material in the survey unit does not exceed the release criteria (NRC 2020b). NUREG-1505, Revision 1, presents a special case of Scenario B in which background variability is considered in establishing a non-zero LBGR.

The NRC guidance focuses on the WRS with Scenario B. However, because Scenario B can be used with the Sign test, it does not necessarily have anything to do with indistinguishable from background. The EPA has submitted a charge review question to the Science Advisory Board on the appropriateness of using Scenario B only for those situations where Scenario A is not feasible (EPA 2020). One of the revisions to MARRSIM was to improve the description of the LBGR as it rephrased the statistical language to "represents a conservative estimate of the remaining residual radioactive material in the survey unit" (EPA 2020).

Currently, the use of Scenario B is expected for only a few facilities. NUREG-1505 provides an example of the use of Scenario B to demonstrate indistinguishability from background when the residual radioactivity consists of radionuclides that appear in background and the variability of the background is relatively high (NRC 1998a). The NRC has also indicated in a draft Revision 2 of Appendix G to NUREG-1757, Volume 2, that Scenario B might be used if there is uncertainty that backfill soils are nonimpacted. The same draft revision to Appendix G to NUREG-1757, Volume 2, contains additional information and other examples for surveys involving Scenario B (NRC 2020c).

Considering that there are published draft revisions to NUREG-1757, Volume 2, and also to MARSSIM, the question becomes what additional information is needed for subsurface soils? Further, Scenario B is not implemented in SADA (Stewart et al. 2009), and identification of software for this purpose remains a software data gap. Although used for 2D applications, VSP does perform Scenario B.

In NUREG-1757, Volume 2, Revision 1, the NRC identifies several precautions to take when using Scenario B for FSS statistical tests (NRC 2006):

- Case-by-case evaluation is required.
- Licensees considering the use of Scenario B for compliance with 10 CFR Part 20, Subpart E, are strongly encouraged to consult with the NRC staff early in the planning process.
- Information about the potential use of Scenario B can be found in NUREG-1505 (NRC 1998a), but the NRC indicates that this scenario should be used cautiously.

It is assumed that the caution applies to the confusing terminology as to how Scenario A is different from Scenario B. Note that the term UBGR does not appear in NUREG-1505; however, MARSAME contains 124 occurrences. The following clarifies some terms from MARSAME (NRC 2009a):

- **Action level (AL)** is the numerical value that causes a decisionmaker to choose one of the alternative actions. In MARSAME, the numerical value is the radionuclide concentration or level of radioactivity corresponding to the disposition criterion, and the alternative actions are determined by the selection of a disposition option.
- **Discrimination limit (DL)** is the level of radioactivity selected by the members of the planning team that can be reliably distinguished from the AL. The lower bound of the gray region (LBGR) for Scenario A and the upper bound of the gray region (UBGR) for Scenario B are examples of DLs. NUREG-1757, Volume 2, Revision 2, does not use the term DL.
- **Upper bound of the gray region (UBGR)** is 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 corresponds to the AL. For Scenario B, the UBGR corresponds to the DL.
- **Lower bound of the gray region (LBGR)** is 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 to the DL. For Scenario B, the LBGR corresponds to the AL.

In Scenario B, the burden of proof is no longer on the individuals designing the survey and thus should be used with caution and only in those situations where Scenario A is not an effective alternative and regulators have agreed on the use of Scenario B. Regardless of the scenario selected, the probability of rejecting the null hypothesis when it is truly false (i.e., the statistical power) will depend on the variability in the survey unit and the tolerable Type II error probability (i.e., β). Under Scenario A, this type of decision error can result in deciding that a survey unit does not meet the release criteria when it actually does. However, under Scenario B, this type of decision error can result in deciding that a survey unit does meet the release criteria when it actually does not. For this reason, the value of β under Scenario B should be chosen carefully and in consultation with regulatory authorities (NRC 2020b).

Because inadequate statistical power under Scenario B can result in a decision error that a survey meets release criteria when it does not, individuals designing a MARSSIM survey using Scenario B should make conservative assumptions for σ so that, even if the variability in the survey unit is higher than expected, the power of the resulting survey ($1 - \beta$) will still be sufficient to ensure that survey units with residual radioactive material in excess of the DCGL will be discovered at least $1 - \beta$ percent of the time. To ensure adequate statistical power, a retrospective power analysis that indicates that regulatory agency requirements on β were met needs to be completed following the Scenario B MARSSIM surveys. MARSSIM, draft Revision 2, Chapter 8 and Appendix I, contain more information on performing retrospective power analyses (NRC 2020b).

For Scenario B, MARSSIM also recommends the quantile test and a retrospective power analysis. These additional tests provide assurance that when the null hypothesis is not rejected, it is not because there is insufficient power in the statistical tests. The retrospective power analysis can also be useful for Scenario A in identifying the reasons why the null hypothesis was not rejected. The tests described in MARSSIM, draft Revision 2, Chapter 8, are relatively easy to understand and implement. A new concept for MARSSIM is ranked set sampling, which is another method for performing statistical testing of samples and can be useful for HTD radionuclides (see MARSSIM, draft Revision 2, Appendix E). For the reasons described above, Scenario A is preferred to Scenario B. Scenario B should be used instead of Scenario A only when there is sufficient justification for its use (NRC 2020b).

For Scenario B, the AL is chosen as the LBGR and the upper bound is the DL, a value that represents how much effort will be taken to determine there is no residual radioactive material (see Figure 9-1). For decision error rates, a value that minimizes the risk of making a decision error is recommended for the initial calculations. The number of measurements can be recalculated using different values for the LBGR, DL, or decision error rates until an appropriate survey design is obtained. A prospective power curve (see MARSSIM, draft Revision 2, Appendix M) that considers the effects of these parameters can be very helpful in designing a survey and considering alternative values for these parameters and is highly recommended (NRC 2020b).

In NUREG-1505 (NRC 1998a), the gray region is defined to be below the AL in both Scenario A and Scenario B. However, in MARSAME (NRC 2009a) and MARLAP (NRC 2004), the gray region is defined to be above the AL in Scenario B. The planning team chooses the DL, which is the concentration of radioactive material or level of radioactivity that can be reliably distinguished from the AL by measurements taken with the devices selected for the survey (i.e., direct measurements, scans, in situ measurements, samples with laboratory analyses) and defines the rigor of the survey (NRC 2020b).

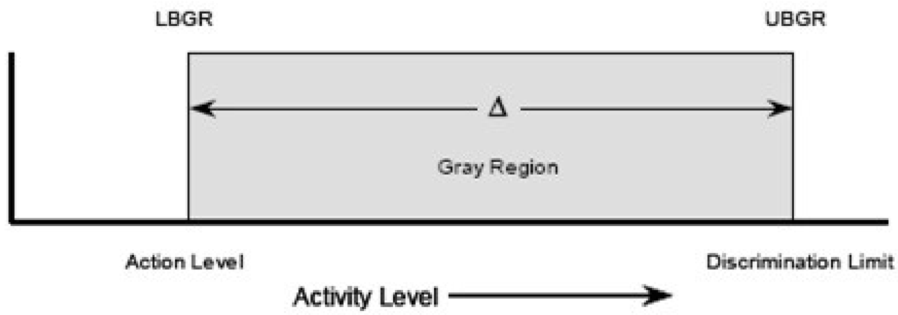

Figure 9-1 Illustration of Scenario B

Source: NRC 2009a, NRC 2020b

10 EVALUATIONS OF LARGE SOIL EXCAVATIONS AND EQUIPMENT

This section describes and evaluates methods used to survey large subsurface soil excavations and soils for reuse in large excavations. Methods include the use of conveyor belts.

KEY POINTS

- Only the NRC has actually applied SADA in a site review, which indicates that the guidance and tools for the industry are yet to be developed.
- There are several instances where a surface DCGLw is applied to excavation sides and bottoms. Questions about the current decommissioning process versus a SADA framework abound, including the following:
    - Except for intrusion scenarios, can users eliminate the DCGLw and switch to a DCGLv?
    - Do licensees correctly identify all areas that need to be remediated? Is SADA better than the current process?
- A review is presented of how several sites (including NPPs) developed DCGLs and how they were implemented.
- How is a conveyorized survey machine used, and what soil sorters are available?
- Lessons learned from the several sites are presented.

MARSSIM provides guidance for determining whether a site is in compliance with a radiation dose or risk-based value (NRC 2000a). Specifically, the guidance is focused on contamination at the surface, either in the top soil layer or on hard surfaces such as buildings.

The EPA's Triad model focuses on decision quality and methods that maximize available information, technologies, and expertise to address and mitigate sources of uncertainty (Stewart 2012). This white paper describes how Triad may extend MARSSIM to the subsurface using a substantial and continually advancing set of tools, including spatial analysis, modeling, and the GIS community. Only the NRC has actually applied SADA in a site review, indicating that the guidance to industry is yet to be developed. How does the NRC move the industry from strict MARSSIM surface precision to acceptance of SADA for the subsurface?

This section reviews (1) several large soil excavations, (2) the survey technology including a principal device, the conveyorized sorting monitor, (3) some of the commercially available devices for larger volume soil sorting, and (4) lessons learned from the reviewed soil excavations. As expected, there are many different scenarios in the RSSI process, but the question is whether the material presented represents all future decommissioning sites. Identification of all licensees and their specific issues with subsurface contamination is important for the NRC to provide the necessary guidance for steps in the entire RSSI process. Particular issues identified during the public comment period or workshop should be included in the NUREG/CR to be drafted.

10.1 EVALUATION OF LARGE SOIL EXCAVATIONS

The anticipated site-specific remediation experience for contaminated subsurface soil can be found in project documents submitted by each licensee such as the LTP, DP, and FSS. The various documents used in this review are identified by facility in Appendix H. This review provides a glimpse of major issues and certain resolutions but does not provide an indepth explanation of the decommissioning approach selected.

Several significant subsurface soil remediation cases are summarized based on the MARSSIM process, including the soil level of concern for the DCGL, computer codes used, excavation description, discussion of any reused soils, notes on dose modeling and surveys, and a discussion regarding the survey process for used soils. These cases include three commercial NPP sites in the United States (Humboldt Bay, La Crosse, and Zion) selected for review of their decommissioning experiences with contaminated subsurface soil. Additionally, six complex decommissioning sites were selected for review of their decommissioning experiences with contaminated subsurface soil: West Valley Demonstration Project, AAR Manufacturing Group, ABB Windsor, Nuclear Fuel Services (NFS), Westinghouse Electric Hematite Facility, and Mallinckrodt Chemical. Appendix H presents these reviews, with summaries presented here.

Dose Criterion (mrem/year)—Most sites were limited to the 25 mrem/year criterion plus ALARA; however, there were multiple variations due to negotiations with stakeholders, State regulation requirements for land transfer, and site-specific subsurface configurations.

Multiple Sets of DCGLs—There were multiple interpretations as to what was surface and subsurface. For example, Hematite used a three-layer approach for the surface (0–15 cm), the root zone (15 cm—1.5 m), and the subsurface (1.5–6.7 m). Some licensees applied a sum of fractions (SOF) approach for multiple radionuclides and zones, although many licensees defaulted to the most limiting DCGL because of the complexity in accounting for multiple layers, radionuclides, and DCGLs. West Valley used a 2.5-mrem/year criterion for sediments, and 22.5 mrem/year for either surface or subsurface soils to address cumulative dose from multiple contaminated media.

$DCGL_{EMC}$—In preliminary reviews of the AAR Manufacturing site, the NRC developed a novel approach to consideration of subsurface residual radioactivity and associated averaging rules. In later reviews, different approach to consideration of elevated areas were considered (e.g., the SADA example in Appendix H for the ARR Manufacturing Group looks at distribution of potential dose based on variability in exposure area concentrations for various size exposure areas).

At some reactor sites, limits for the maximum concentration of elevated areas (similar to the $DCGL_{EMC}$) were developed for contaminated concrete surfaces considering various intrusion scenarios. In one case, the potential doses to a well driller who drills through the elevated area and a resident farmer who is exposed to the evacuated spoils were considered.

Scenario/Initiating Event/Pathways—Sites considered the limiting exposure scenario as the Resident Farmer, Resident Gardener, or Industrial (e.g., for large reactor basement substructures).[20] One site considered offsite doses to a potentially sensitive critical group (Native American population) from eroded sediments released to surface water. For buried residual radioactivity at depth, an intrusion scenario was often considered to bring residual

[20] In one case, the recreational scenario was considered for surface water sediments because of the inability to construct a residence on such a terrain.

radioactivity to the surface (e.g., basement construction or well drilling associated with a resident scenario).

For some sites, the ground water pathway was most important to dose in deriving subsurface DCGLs and more sophisticated modeling needed to be used (e.g., at West Valley, backwards diffusion of residual radioactivity from low-permeability layers upwards into the water table aquifer was found to be more limiting for many radionuclides than the cistern excavation scenario).

Software Codes Used—In all cases, the Residual Radioactive in Soils (RESRAD) family of codes was used to develop DCGLs. Survey designs and DCGL support were developed with software such as GMS, SADA, MicroShield, MCNP, VSP, WEPP, Siberia, CHILD and other custom or off-the-shelf codes. While RESRAD-ONSITE is typically used to develop DCGLs, various codes are applied for more complex contaminant fate and transport modeling and erosion modeling, and to account for shielding. Codes such as VSP are used for survey design.

Survey of Excavations and Underlying Soils—Lessons learned from some sites were related to inadequate surveys of surfaces of excavation bottoms or walls. Survey of soils below the excavation may also be needed, particularly if there is known ground water or deep subsurface contamination. At one site, a reactor licensee sampled subsurface soils directly below the reactor basement structure using soil borings or Geoprobe® sampling biased to locations having a high potential for the accumulation and migration of radioactive contamination. At other sites, the NRC staff noted inadequate sampling of deep subsurface soils below excavation bottoms and of ground water with existing contamination of ground water providing evidence of radionuclide leaching to deep subsurface soils.

Reuse of Soil—If DCGLs are developed for soil reuse, soils at less than the DCGL could return as backfill, while soils above the DCGL are typically sent to an offsite facility. For example, Hematite's policy was to reuse soil only if it was "clean" after gamma scans (portal) and sampling. In other cases, soils that were contaminated at a fraction of the DCGL could be used (e.g., 50 percent of the DCGL). Some sites indicated no reuse of excavated soil but were filled with "clean" material, although the presence of residual radioactivity in reused soils assumed to be "clean" was questioned at some sites. Humboldt reused a significant volume of soil but did not always survey it adequately. Inadequate surveys were the source of many requests for additional information. Some concerns were related to lack of scanning of reused soils (e.g., soils were not scanned before reuse consistent with their classification, the thickness of the scanned layer prevented adequate survey of residual radioactivity at depth, or the scan speed was not sufficiently slow to meet scan MDC requirements). In all cases, if backfill soils are used to fill excavations, the NRC expects the risk associated with the reused soils to be considered in demonstrating compliance with LTR criteria and the appropriate DCGLs to be used consistent with the dose modeling assumptions.

Reuse of Concrete—Similar to reuse of soil in excavations, some reactor sites reused concrete rubble to fill open reactor basements as part of the final configuration of the site. In some cases, the scan MDCs for the concrete rubble were relatively high in comparison to the DCGL. In those cases, the licensee added the dose contributions of the concrete rubble at the scan MDC. Lessons learned from review of FSSs at some sites also revealed issues with lack of adequate scanning of reused concrete before backfill of reactor basements.

Sampling of Hard-to-Detect Radionuclides—In some cases, adjustment of the core hole density was necessary to account for potentially elevated volumes because of the inability to scan for HTD radionuclides in the subsurface. At some sites, surrogates were established for HTD radionuclides. The process involves evaluating existing data and determining appropriate ratios. Guidance, such as NUREG-1757, Volume 2, Revision 2 (NRC 2020c), is available on the use of surrogate radionuclides.

Dose Modeling and Survey Notes

- AAR—The NRC prepared a novel approach for surveying various depths and averaging natural thorium. Hot spots are less of a concern for this site because of averaging of time spent on any portion of the site (external dose dominates the dose). If the concentration in the exposed 1–2-m interval exceeded the 1–2-m cleanup level of 20 pCi/g total thorium, then the 1–2-m interval would also be removed. Four samples were taken in each 100-m^2 area to calculate the average for the interval.

- ABB Windsor—Portable hand-held gamma instruments were used for soil surveys.

- Hematite—Scan of sidewalls was required. The scan speed was very slow and the height was very close to the surface, according to MARSSIM standards, because of an initial failure to detect uranium pellets.

- Humboldt Bay NPP—Multiple samples were collected from the surface and bottoms, and the excavation bottom was scanned. The backfilled soils were only scanned, not sampled.

- La Crosse Boiling-Water Reactor—A gamma walkover survey of excavated surface with EMC was performed.

- Mallinckrodt—A standard FSS was required.

- NFS—Surrogates were established for HTD radionuclides. The safety evaluation report describes the process for adjusting, or considering adjustment of, the core hole density to account for potential elevated volumes. The process involves evaluating existing data and determining reasonable maximum and expected maximum concentrations (90th percentile and maximum).

- West Valley—The DOE will survey the soils at the bottom of the excavation (top of lavery till) to verify the thickness and concentration of residual radioactivity to ensure consistency with the dose modeling assumptions used to derive DCGLs. For example, the DOE assumes that the residual radioactivity is diluted by a factor of 10 with overlying clean soil for the intrusion scenario (drilling of cistern); therefore, the thickness of residual radioactivity remaining at the bottom of the excavation can only be one-tenth of the thickness of the overlying clean material. Ground water pathways were also considered for buried residual radioactivity (diffusion of residual radioactivity back into the water table aquifer) and found to be most limiting in most cases.

- Zion—Section 5.7.1.6.3 of the LTP discusses sampling of subsurface soils below basement structure foundations. Strategies to sample subsurface soils below basement structures include soil borings or Geoprobe® sampling and will be biased to locations with a high potential for the accumulation and migration of radioactive contamination. Any detection of residual radioactivity in subsurface soils adjacent to or under a basement surface will result in an investigation to assess the potential contamination of the exterior of the structure.

10.2 SOIL-SORTING EQUIPMENT FOR LARGE SITES

The regulatory release of sites for restricted or unrestricted use employs conservative approaches and dose models to ensure that release criteria are not exceeded. Certainly, subsurface soil concentrations, which cannot be readily scanned in an "as-is" state, present the potential for application of overly conservative criteria and an unwarranted costly remediation process for transport and burial of contaminated soil that is actually below the release criterion.

Soil-sorting technology may be part of the answer to this issue for large sites with subsurface contaminated soil. The goal of the segregation process is to produce stockpiles below and above a criterion optimized for maximum refill and minimum waste. Material that is below criteria is returned to the excavation, while the material above the criteria is packaged for offsite disposal (Lombardo et al. 2007).

10.2.1 Conveyorized Survey Monitors

NUREG-1761, "Radiological Surveys for Controlling Release of Solid Materials," issued July 2002, provides general insight into the characteristics, design, and application of conveyorized survey monitors (NRC 2002). They offer a form of automation that may be particularly well-suited for use when significant quantities of bulk material are subject to clearance requirements. As the name implies, these systems operate by moving materials past radiation detectors using a conveyor system, while automatically storing and analyzing the resulting signals. The radiation detectors themselves can be of any type and are chosen to match the application. The most common detectors in use are NaI crystals for gamma detection and thin-window proportional counters for beta detection. Appendix I provides additional information on automated data processing and detectors used with conveyorized survey monitors.

10.2.1.1 Detection Sensitivity

The selection of detectors and supporting electronics is the key to optimizing overall system performance for specific applications. Other parameters that should be considered include the quantity and placement of detectors, as well as the speed of materials passing the sensitive regions of the detector(s). Appendix I gives additional information on the following topics:

- detection efficiency for gamma-emitters using NaI detectors
- detection efficiency for beta-emitters using thin-window proportional detectors
- conveyorized survey monitor scan MDCs

10.2.1.2 Conveyorized Survey Monitor Survey Design Considerations

Conveyorized survey monitors are expected to be used in conjunction with other survey methods during the release of materials for unrestricted use. These relatively massive devices are primarily designed for scanning applications; however, it is possible to construct control algorithms that combine a number of complementary survey stages. Examples include the combination of different detector types, scan and static measurement modes, and the ability to make parallel decisions based on various combinations of measurement results. Ultimately, it is expected that conveyorized survey monitors could be applied as an advanced, automated scanning process in lieu of using hand-held equipment. Additional information on this topic is also provided in Appendix I.

10.2.2 Commercially Available Equipment

Soil-sorting equipment is important during decommissioning, and an internet search was made to determine how many and what kind of systems are commercially available. The reader should note that the identification of these survey instruments or equipment does not, in any way, constitute endorsement of a particular product or manufacturer by the NRC or its contractors. Appendix J presents the reviewed vendors and a brief description of their product in alphabetic order. Claims made in the descriptions are from the vendor and not endorsed by the NRC. Certainly, any large-volume soil-sorting equipment not yet identified but presented during the public comment period or the public workshop will be included in the NUREG/CR to be developed.

10.3 LESSONS LEARNED ABOUT SUBSURFACE RADIOACTIVITY

As stated above, AAR applied a $DCGL_W$ to excavated bottoms and removed soil greater than the $DCGL_W$. AAR also excavated at the 1–2-m interval for higher concentrations to ensure that the average concentration in the 1–2-m interval met the cleanup criteria. NFS performed coring and sampling on 50-m^2 grid nodes. Mallinckrodt performed an FSS of excavations. These examples indicate that licensees are making MARSSIM-like surface surveys of subsurface soils. Note that four of the reviewed sites did not reuse excavated soil, while Mallinckrodt permitted backfill if excavated soil was less than the DCGL.

Excavation experiences across the industry show inconsistency in how facilities handle layers or volumes that are just above the DCGL. It also appears that most apply the surface $DCGL_W$ to individual excavation layers without taking credit for mean concentrations from the use of backfill. As licensees must address the cumulative impacts of all source areas to demonstrate compliance with LTR criteria, they must determine which DCGLs are applicable and whether it is appropriate to remove slightly higher contaminated soil volumes (hot spots) without averaging. This section addresses several excavation and modeling issues, but a topical MARSSIM roadmap for all licensees is not identified.

Following are examples of other lessons learned.

10.3.1 Lessons Learned Related to Dose Modeling

(1) Because decommissioning activities for complex sites often take a long time to accomplish and may be conducted in phases, the licensee must demonstrate that decommissioning criteria are met for the entire site at the time of license termination, including previously remediated areas. The licensee must address the cumulative impacts of all source areas to demonstrate compliance with LTR criteria and must consider this in its development of DCGLs. Lower DCGLs may need to be set for a particular media to ensure that the dose limit can be met for multiple sources that may cumulatively contribute to dose. For example, West Valley performed phased decommissioning and developed DCGLs in Phase 1 when it considered how multiple source areas could cumulatively add to the dose at a particular exposure point (e.g., offsite dose to a member of the Seneca Nation of Indians critical group). Additionally, a fraction of the 25 mrem/year dose limit for unrestricted release was fractionated to account for the contributions of surface soils and streambed sediments to total dose to a potential resident. Zion and the La Crosse Boiling-Water Reactor developed operational DCGLs for each source type to alert surveyors when more attention to an area (volume) was required.

(2) The depth of contamination limits accessibility to and potential exposure from residual radioactivity due to attenuation of external radiation via the overlying soil column, limited upwards transport of nonvolatile radionuclides to the surface, lack of uptake of residual radioactivity in vegetation, as well as limiting mass loading of residual radioactivity to air. Therefore, intrusion scenarios that can bring the radioactivity to the surface where members of the public can be more readily exposed are often considered for buried radioactivity. In these scenarios, concentrations of residual radioactivity and thickness of cover and waste are important to the calculations. Other important factors affecting the likelihood and nature of the exposure include the presence of natural resources, local drilling practices, and the presence of intruder barriers. When residual radioactivity is located at depth, the ground water pathway can also be the most limiting pathway for more mobile radionuclides. For the ground water pathway, the total inventory is often important to risk. The depth of residual radioactivity (or vadose zone thickness) can also be an important consideration in dose modeling.

(3) Assumptions regarding the distribution of drill cuttings on the surface are often important to development of subsurface soil DCGLs. In past performance assessments and decommissioning dose modeling exercises, sensitivity analyses were conducted in response to requests for additional information and revealed that the dose could differ by up to a factor of 10 depending on the dose modeling assumptions. Assumptions should be adequately justified or uncertainty managed with realistically conservative assumptions.

(4) The thickness of residual radioactivity at the surface is strongly correlated to dose for certain radionuclides (e.g., those dominated by the plant ingestion pathway). The thickness of residual radioactivity should not be underestimated in the modeling, or the dose may be significantly underestimated. If the thickness of residual radioactivity is much smaller than assumed in the dose modeling, the DCGL may be overly restrictive. It is important to understand the modeling assumptions and how well they match reality and the final status of the site.

(5) If subsurface residual radioactivity at depth has a higher concentration than in surface soils, understanding erosion rates, which could make the subsurface residual radioactivity more accessible, could be important to the compliance demonstration.

(6) In cases where surface concentrations are higher, the erosion rate in RESRAD-ONSITE can be important to dose. RESRAD-ONSITE does not consider erosion as a source of residual radioactivity in offsite locations. Instead, it assumes that erosion is a removal mechanism of radioactivity from the model. The default erosion rate[21] in RESRAD is 0.001 m/year. If a decay chain is in disequilibrium, the surface soils may be eroded away before significant in-growth of daughter products, thereby significantly underestimating the dose compared to use of a lower erosion rate.

(7) All transport mechanisms and scenarios should be considered, as it is difficult to determine which scenario may be more limiting. For example, at West Valley, contaminated subsurface soils will be removed below the water table to the top of the lavery till, a low permeability subsurface layer. It was assumed that the intrusion scenario would be most limiting. However, during the request for additional information process, it was determined that diffusion of residual radioactivity back into the overlying

[21] If the default value is used, a 1-m thickness of residual radioactivity will be eroded and removed from the model during the 1,000-year compliance period.

sand and aquifer unit was more limiting, given the importance of the ground water pathway for certain key radionuclides.

10.3.2 Lessons Learned Related to Characterization

(1) Because of the complexity of characterizing subsurface residual radioactivity that cannot be surveyed without disturbance of the soil, GIS and geostatistical tools can be useful in developing a conceptual model and distributions of known residual radioactivity and extrapolating data to areas where no data exist. Modeling can also be useful for determining potential transport pathways and areas that are most likely to be impacted by site operations. Probabilistic and statistical methods can also be employed to determine the most probable areas of residual radioactivity and can thereby be used to develop sampling plans to guide scoping, characterization, remediation, and FSSs. Final distributions of residual radioactivity created through geospatial modeling can also be used in dose modeling to estimate the final predicted dose to potential receptors. The NRC is developing revised guidance on use of tools in Section 8.2.2.2 of MARSSIM that can be used to help characterize subsurface contamination.

(2) For sites where decommissioning and remediation occur over a long period of time, it is important to ensure that previously cleaned areas do not become recontaminated because of transport of residual radioactivity from unremediated areas into remediated areas (e.g., surface water runoff, additional discharge or seepage of contaminated ground water to surface water, and recontamination of stream sediments). Some confirmation that previously remediated areas have not been contaminated should occur at the time of the FSS for the entire site.

(3) Additionally, for complex sites undergoing phased decommissioning, the collection of additional information over a long decommissioning period may reveal that risks are significantly underestimated or modeling assumptions are otherwise invalid. In these cases, the NRC expects that the impact of these events on the ability of the site to meet LTR criteria would be evaluated. The licensee may need to conduct routine monitoring activities or additional studies to address key uncertainties (e.g., West Valley’s ongoing assessment period) to ensure that risks are appropriately managed and studied.

(4) For complex sites, early and frequent communication with the regulator can help increase efficiency and likelihood of success. Determining an acceptable approach in advance of performing the radiological surveys can help limit risk associated with resampling or more costly reviews and surveys late in the process. The licensee should also ensure that it is following the agreed upon approach throughout the site decommissioning.

(5) No matter the outputs of soil scanning, the regulators will want some level of representative sampling of the radionuclides of concern (ROCs), especially if the ROCs are HTD versions or the ratios among ROCs vary. If the output is two or more soil stockpiles (one for waste and another for reuse on site), appropriate shipping and characterization data are necessary, and for reuse, comparisons to DCGLs will be made.

10.3.3 Lessons Learned Related to Dose Modeling

(1) If subsurface soil DCGLs are developed, the assumptions in the dose modeling should be generally consistent with the FSS of the residual radioactivity. For example, if it is assumed that a certain thickness of cover is present over the residual radioactivity, then

the FSS should confirm that thickness (e.g., if the dose modeling assumes that clean backfill is used to fill an excavation, use of subsurface DCGLs developed for the bottom of the excavation should not be used to segregate excavated soils for potential reuse). The assumption regarding thickness of cover impacts the calculation of dose at the surface for undisturbed soil, as well as dilution of residual radioactivity that is brought to the surface from an intrusion event. The thickness of residual radioactivity remaining at the site should also be consistent with the dose modeling (the thickness also impacts the concentration of material brought to the surface and inventory available for the ground water pathway).

(2) Significantly higher DCGLs may be approved for subsurface soils and should not be used for soils used to fill the excavation, especially near the surface. The contribution to risk from various strata should be considered if multiple sets of DCGLs are developed. It is always prudent to perform dose modeling using the final configuration of residual radioactivity to determine if the radiological criteria for license termination are met.

(3) If surface soils are more concentrated than subsurface soils, care should be taken to ensure that the sampling design does not lead to an underestimate of concentration and dose (e.g., for radionuclides dominated by the external dose pathway, the concentration at the surface is most important to dose and should not be diluted with cleaner material at depth). Depth discrete sampling may be necessary to determine soil concentrations in smaller intervals consistent with important dose modeling assumptions and pathways.

10.3.4 Lessons Learned Related to Remediation

(1) If contaminated ground water is an issue, initial efforts should focus on identification and elimination of the source. Once the source is eliminated, life cycle remediation needs and associated costs can be more accurately determined (Sullivan et al. 2011).

(2) Hot spot removal in the ground water for mobile contaminants should be done as soon as possible. Delays can lead to a longer and more complicated cleanup (Nicholson et al. 2011, Sullivan et al. 2011, and Abu-Eid 2012).

(3) It is useful to compile a database of representative data as a soil stockpile is being built for reuse. The database can be potentially used for FSSs, and it also can serve as a baseline so that, if a soil stockpile is present during decommissioning activities, a few additional surface samples can be taken to demonstrate that the stockpile was relatively unaffected by site activities before its use.

(4) While sampling material to make up a soil stockpile, if a case can be made that it is well-mixed material, obtaining composite samples from surface soil as the stockpile is generated may give a more representative result than sporadic grab sampling.

(5) If cross-contamination of already remediated areas is possible, then consideration of the order in which the FSS is performed becomes important. For example, if the potential exists for a survey unit that has already received an FSS to become contaminated, the class of the survey unit may need to be decreased, and a resurvey of the survey unit may be required.

(6) The walls and bottoms of excavations always need to be surveyed adequately before backfilling. Hematite skipped whole parts of the wall in its scanning (because in its view, these areas were “inaccessible,” even though a detector could have been put on a pole).

Hematite backfilled the excavation before this issue could be addressed, so what should have been an easy fix became complex.

11 AUTONOMOUS VEHICLES SCANNING METHODS AND TECHNIQUES

Unmanned ground vehicles are classified into two broad types, remotely operated and autonomous. Autonomous unmanned ground vehicles comprise several technologies that allow the machine to be self-acting and self-regulating, sans human intervention. This review focuses on the autonomous ground vehicles (AGVs), with operators perhaps intervening when necessary. This review does not include surveys with airborne drones.

Although gamma walkover scan surveys and staffed driveover surveys have been the norm, recent developments in technology now permit AGVs to be used to perform deep subsurface surveys over relatively smooth terrain, and perhaps on relatively steep slopes and narrow benches in excavations. This review considers equipment proposed for outdoor radiation mapping and sampling beyond those GPS-based detector systems carried by technicians or mounted on pushcarts, manned vehicles, or radio-controlled vehicles. It does not include platforms considered to be too large to work on excavated benching.

KEY POINTS

Draft MARSSIM Revision 2 includes the possibility for scanning surveys without systematic physical sampling to demonstrate that concentrations of radioactive material do not exceed release criteria.

- AGV technology may be useful for scan surveys but at this point this use is unproven. Steering is preprogrammed or aimed at a “way point.” Some operations are controlled by nearby operators. The ability to scan slopes and benches in the open trenches has not been tested.
- The technology has been commercialized on a limited basis.
- AGVs could aid in meeting Occupational Safety and Health Administration (OSHA) safety considerations and serve as an ALARA tool.

11.1 OPPORTUNITIES OFFERED BY AUTONOMOUS RADIATION SURVEY PLATFORMS

11.1.1 Background

Current NRC practice for remedial work of subsurface areas is to perform gamma ray surveys for designated 6-inch layers at each excavated layer within the pit, or the material is spread in a 6-inch layer outside the pit area and surveyed or stockpiled for survey later (NRC 2020a). As discussed in Section 10, some licensees have used soil-sorting technology for large sites with contaminated subsurface soil in order to produce stockpiles of segregated soils below and above a criterion optimized for maximum refill and minimum waste. Often, the stockpiles are resurveyed after being spread in 6-inch lifts (NRC 2020c). Further, the sidewalls and benches in trenches must often be surveyed, where simply walking on the surfaces could present a physical hazard to a worker.

MARSSIM, draft Revision 2, permits the use of scanning techniques without physical samples for demonstrating that concentrations of radioactive material do not exceed release criteria. The scan MDC and measurement method uncertainty must be sufficient to meet measurement quality objectives (MQOs) to both quantify the average concentration of the radioactive material and to identify areas of elevated activity. In addition, scanning equipment must be coupled with GPS or other locational data equipment. Maintaining the specified source-to-detector distance and speed during scanning can be difficult on irregularly shaped surfaces. Any variations in source-to-detector distance and scan speed can result in increased total measurement method uncertainty. Calibration functions for surficial radionuclides uniformly distributed on a plane can be complicated, modeling must establish a field of view, and total measurement method uncertainty must be determined (NRC 2020b). Routinely, a field of view is determined, and the scan rate and path width are adjusted, depending on the expected detector response and the desired investigation level.

Mapping surface or subsurface radiation levels in challenging environments, such as extremely rough terrain; other unsafe environments for ground personnel, such as unexploded ordinance (UXO) areas; or sensitive areas where necessary soil and vegetation disturbance, must be performed in a manner that will satisfy both stakeholders and regulatory requirements. OSHA has made the reduction of trenching and excavation hazards a priority goal[22] as trench collapses, or cave-ins, pose the greatest risk to workers' lives. Means to prevent cave-ins include sloping or benching trench walls and testing for atmospheric hazards such as low oxygen, hazardous fumes, and toxic gases when excavations are more than 4 feet deep. Employers must also ensure there is a safe way to enter and exit a trench, in accordance with 29 CFR 1926.651, "Specific excavation requirements."

Figures 11-1 and 11-2 illustrate the complicated trench designs for cohesive soil; surveying the bench and slope for all types of soil could be hazardous to a worker.

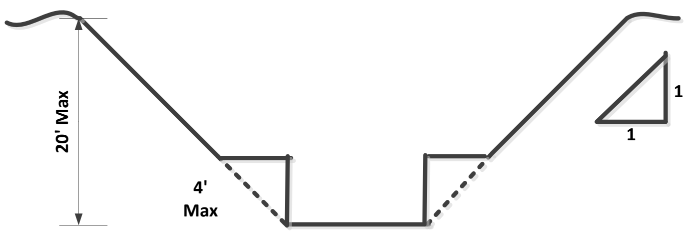

Figure 11-1 Allowable Bench in Cohesive Soil

Source: 29 CFR Part 1926, "Safety and Health Regulations for Construction," Subpart P, "Excavations," Appendix B, "Sloping and Benching"

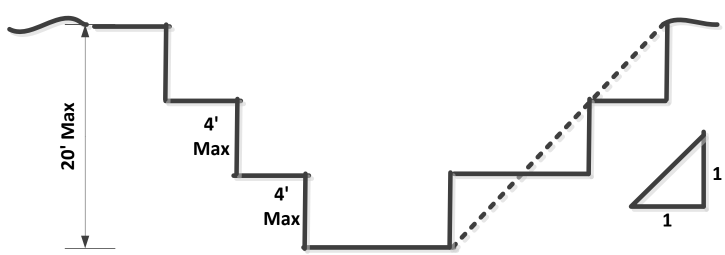

Figure 11-2 Allowable Benching in Cohesive Soil

Source: 29 CFR Part 1926, Subpart P, Appendix B

22 Proper excavation safety practices should always be applied in accordance with OSHA, requirements, such as the use of support systems, and/or sloping and benching, to stabilize the excavation site. Refer to the US Army Corps of Engineers, Safety and Health Requirements Manual EM 385-1-1 for additional details.

11.1.2 Potential Role for Autonomous Radiation Survey Platforms

In 1994, the DOE received U.S. patent number 5,324,948, entitled Autonomous Mobile Robot for Radiological Surveys. Since then, accessibility to an area has been maximized or implied risk to a survey team minimized by using autonomous or unmanned vehicles in limited applications to map and monitor radioactive sites.

AGV surveys offer improved survey design and quality over walkover surveys in that the former can attain a near-constant survey speed, eliminating stumbling or inconsistent walking speeds; therefore, time intervals over a specified area are better controlled. AGV surveys also result in lower uncertainty related to average detector survey heights as they eliminate the height changes caused by the pendulum-like swinging of the detector during walkovers. As uncertainty regarding survey height and speed is also better controlled than that with a walkover scan, MQOs can be better defined.

Other characteristics of an AGV survey include the following:

- When an elevated area is identified, an operator may intervene, and remote control might be used for a slower speed and direction to fully characterize the elevated area.
- GIS technicians interpret data after the AGV survey; rather than interrupting the base survey, the resurvey of an elevated area would be conducted later.
- Preprogrammed paths may be used to cover medium-size open areas in excavation pits free of obstacles.

AGV surveys could be used to reduce risk to workers on slopes and in bench areas. However, the review of data for available AGV systems for this report did not identify any test results on slope climbing ability or how close a survey unit could get to an edge. In addition, although some survey meters have explosion-proof housing for extreme environments, none have been identified for application in an AGV survey; a competent person at the site would have to decide when entry by an AGV is appropriate.

11.2 AUTONOMOUS RADIATION SURVEY PLATFORMS

The radiation survey and mapping industry has developed the technology behind AGVs with GPS and radiation survey equipment, and such technology is now advertised as available for use. However, a limited number of autonomous radiological survey platforms are currently available that can be used to conduct radiological site characterization, assist with remediation efforts, or conduct site clearance in accordance with MARSSIM. These systems include inorganic scintillators, light detection and ranging, global positioning, inertial guidance, wireless telemetry, and signal processing systems. They work with various types of vehicles, from small battery-powered vehicles capable of carrying one detector to small tractors and skid steers with pull-behind wagons capable of carrying multiple detectors for larger scan paths. Some include the option to identify isotopes through regions of interest and to set a constant speed to meet survey design objectives and MQOs.

Platforms include the collection of radiological and positional data and transmission back to the central computer system in real time. Collected data are saved to a database for postsurvey analysis or can be analyzed in real time. Analysis of the radiological data is used to construct radiation intensity and estimated concentration maps. Automatically generated reports for each survey unit provide survey managers with survey coverage data maps, estimated concentration maps, and a detailed list of elevated concentration areas that are above a user defined concentration. The sections below describe three example platforms.

11.2.1 Institute for Clean Energy Technology

The Mississippi State University's Institute for Clean Energy Technology (ICET) Radiation Detection and Measurement Division, funded by the DOE, U.S. Department of Defense, and the U.S. Army Corps of Engineers, developed innovative radiological detection and mapping systems to locate, map, and recover fired armor-penetrating depleted uranium munitions. The platform includes high-end gamma ray spectrometers and global position sensors for the accurate mapping of radiation fields (Unz et al. 2019).

This platform provides a safety net for technicians where the magnitude of the hazards, including those that are not necessarily radiological, is unknown. For example, the U.S. Army Corps of Engineers deploys autonomous designed systems to detect remnant depleted uranium material on firing ranges where depleted uranium rounds have been used. Many firing ranges have UXO, which poses challenges for conducting walkover or driveover surveys. The combination of active depleted uranium-impacted firing ranges and UXO makes conducting site characterization surveys very difficult and hazardous (Unz et al. 2019). Use of these devices in areas where radiation levels are unknown should be considered an ALARA tactic to prevent radiation exposure.

Figure 11-3 shows the survey platform, while Figure 11-4 illustrates a layout of the working components.

Figure 11-3 Photograph of 1-m Robotic Platforms

Source: Unz et al. 2019

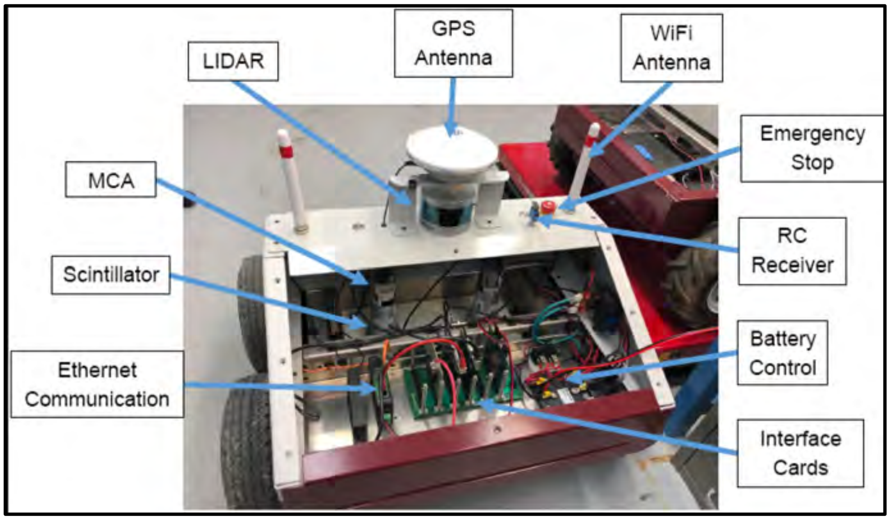

Figure 11-4 Photograph of Components

Source: Unz et al. 2019

Unz et al. (2019) reports that a variety of software packages are used in combination on the robotic platforms and the remote base station computers. The example shown in Figure 11-5 from Unz et al. (2019) includes the following software used together to automate the surveying process, collect and store the data, and manage the system:

- Linux—Ubuntu Server 18.04
- ROS Melodic
- QGIS 2.18
- PgAdmin 4
- PostgresSQL 10
- Modified Open Source IMU Software
- Modified GPS Software
- custom written sensor, motor controller, survey, and localization software

Ubuntu Server is used as the main operating system on each of the platforms. ROS Melodic serves as the backbone for the robotics and automation portion of the platforms. It simplifies the communication and coordination between systems and allows for simple scaling in the future. QGIS and PgAdmin are used on the base station computer to facilitate the geomapping and waypoint creation for the platforms. Through QGIS, system users specify a polygon area to be surveyed. Custom algorithms are used to create survey lines for the platforms to traverse. The survey lines can be divided up and assigned to specific platforms to complete the survey. PgAdmin is used to manage the PostgreSQL database that stores the surveyline/GPS and radiological data. Figure 11-5 provides a flow block diagram of the software and hardware integration.

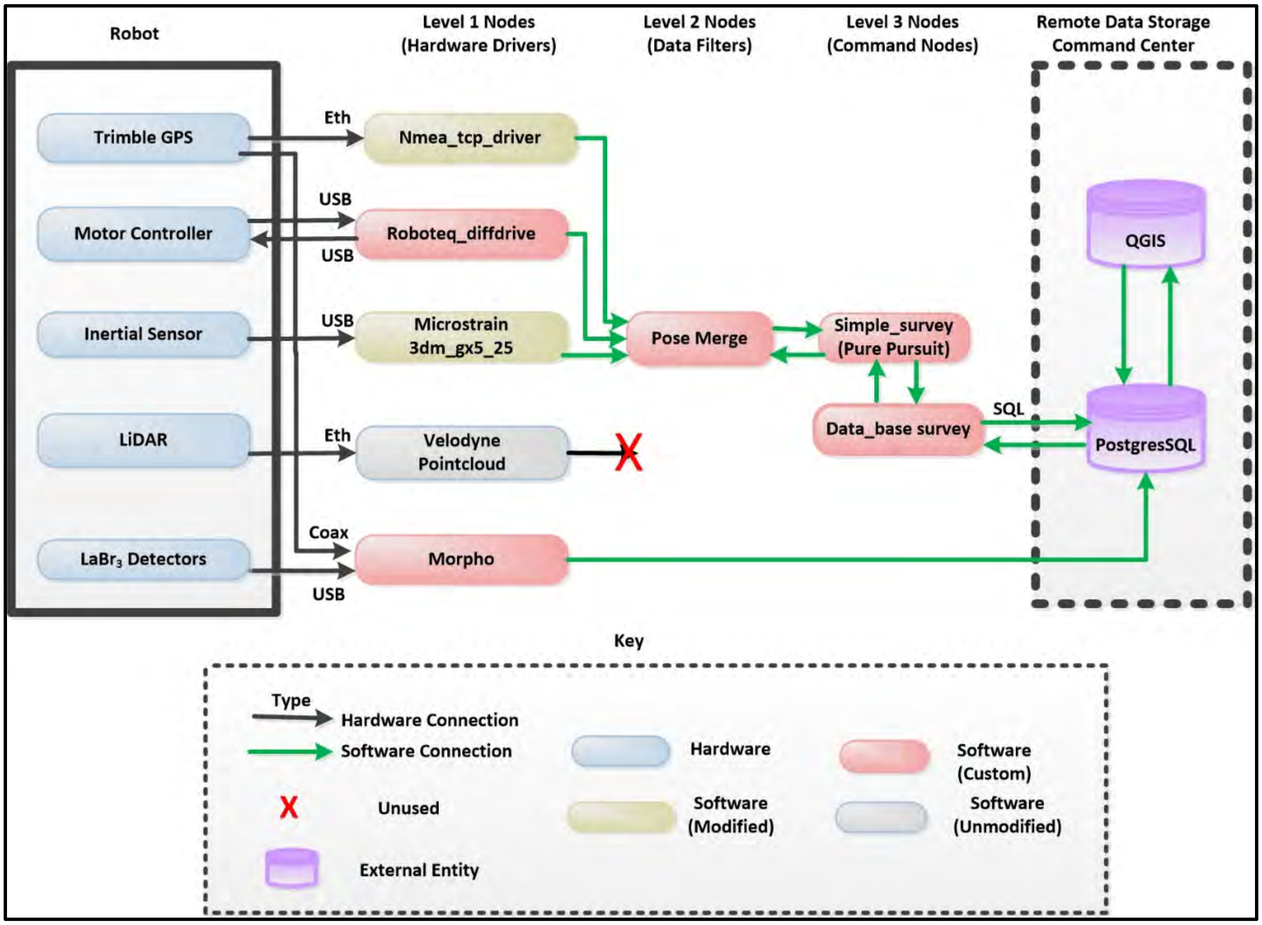

Figure 11-5 Block Diagram Providing a Visual Overview of Software

Source: Unz et al. 2019

Unz et al. (2019) indicates that a key component of the platform is the pure pursuit algorithm, which is a path-tracking algorithm designed to have the robot always “chase” a point in front of it. This point is always located on the line of the path to be traversed. A lookahead distance variable that specifies the distance ahead that the robot should look is used to compute the correct angular velocity. Tuning this parameter can alter how the robot behaves and is the main variable to change when adjusting the behavior of the system. Figure 11-6 gives an example of the effects that the lookahead distance can have on the system.

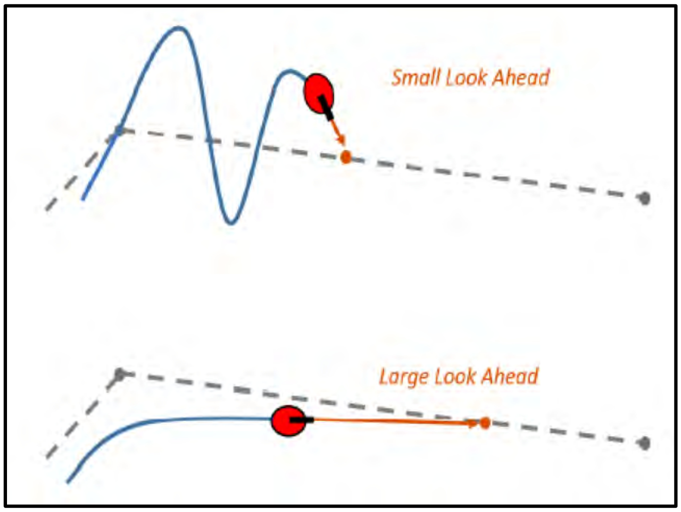

Figure 11-6 Pure Pursuit Algorithm

Source: Unz et al. 2019 (taken from MathWorks, "Pure Pursuit Controller," https://www.mathworks.com/help/nav/ug/pure-pursuit-controller.html)

11.2.2 Florida International University

The Applied Research Center of Florida International University (FIU) presented work on an autonomous radiation mapping and quantification using a UGV at the Interregional Workshop on Optimization of Technology Selection for Decommissioning of Large and Small Nuclear Installations in 2019 (FIU 2019). This research was supported by various offices of the DOE and the National Science Foundation. The goal of the research project is to design a mobile robotic system to support deactivation and decommissioning activities by developing continuous stochastic models using Gaussian processes to predict the overall radiation field by simultaneously fusing data from nondestructive gamma measurements, surrounding images, and three-dimensional LiDAR (light detection and ranging) mapping.

Figure 11-7 shows the configuration of the FIU unmanned ground vehicle.

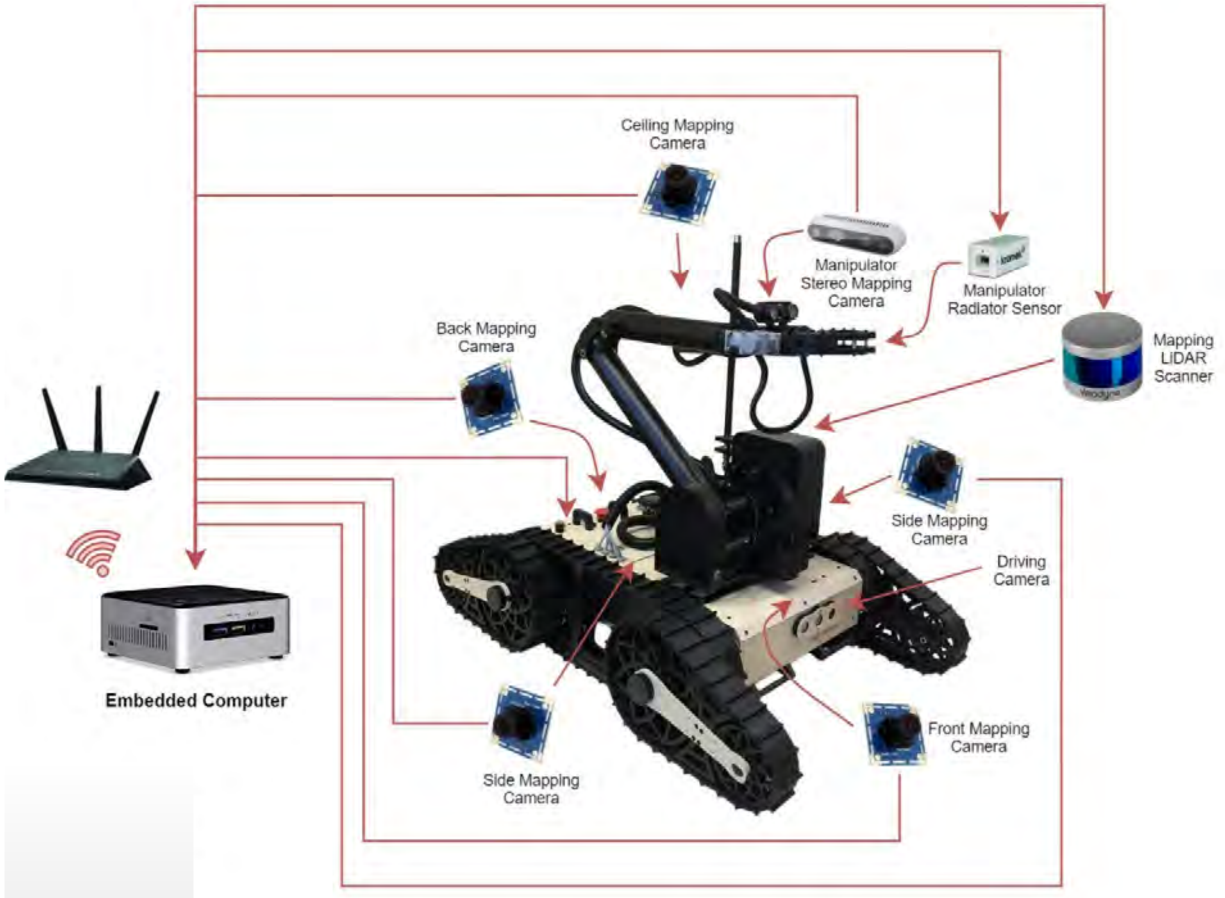

Figure 11-7 FIU Unmanned Ground Vehicle Showing Component Parts

Source: FIU 2019

11.2.3 Kromek UGV Radiation Mapping Rover

Figure 11-8 depicts a commercially available UGV called the RadRover (Kromek 2021).[23] The manufacturer claims that it offers the following benefits:

- The RadRover offers real-time location measurement and mapping of radioactivity with isotope identification using a small ground vehicle.
- When deployed for site surveys on unmanned vehicles, the RadRover effectively reduces worker exposure to radiation because the operator remains at a remote distance. The RadRover can also be preprogrammed for autonomous area surveys.
- The payload bay contains either one or two Kromek gamma spectrometers and positioning devices using custom-built software to combine radiation intensity and geolocation data to produce maps of radiation levels and identification of isotopes present.

[23] A video of the vehicle in action is available at https://www.kromek.com/radiation-mapping-drone/.

Figure 11-8 Kromek UGV Radiation Mapping RadRover

Source: UGV Radiation Mapping Rover (Kromek 2021)

The small, four-wheeled RadRover is designed for rough terrain but is light enough to be lifted by one person and can be carried in a car. Typical RadRover weight is less than 1.5 kilogram (3.3 pounds). Its onboard sensors include a multiband GNSS receiver (GPS, GLONASS). Readings include latitude, longitude, altitude, and uncertainties and temperature, pressure, and humidity. It contains an embedded real-time clock (Internet-connected units synchronize time with NTP servers) as well as a nine degrees of freedom inertial measurement unit (accelerometer, gyroscope, magnetometer).

Multiple gamma spectrometers can be connected to the RadRover and work simultaneously. The unit can use the following:

- Kromek GR1 10 x 10 x 10 millimeter cadmium-zinc-telluride-based detector; energy resolution at 662 kiloelectron-volts (keV) (21 degrees Celsius operation) and less than 2.5 percent full width at half maximum; energy range 30 keV–3.0 megaelectron volts (MeV)
- Kromek SIGMA 50 25.4 x 25.4 x 25.4 millimeter cesium iodide (activated with thallium) scintillation radiation detector; energy resolution at 662 keV (21 degrees Celsius operation) and less than 7.2 percent full width at half maximum; energy range 50 keV–1.5 MeV

The gamma spectroscopy and mapping software shows counts per second and location, counts per second over time, energy spectrum, dose estimation, and isotope characterization, providing a picture of the radiation spread over an area.

Setup and training for the RadRover provided by the company includes operating system maintenance, operational concepts, mission planning, and use of the software.

This UGV is also offered by SciWise Solutions Inc. (SciWise 2021).

12 TREATMENT OF UNCERTAINTY AND DATA SUFFICIENCY

The statistically rigorous quantitative application of measurement quality objectives (MQOs) plays a central role in the design and analysis of the radiological measurement process. However, MQOs did not appear explicitly in MARSSIM, Revision 1 (NRC 2000a), but were subsequently developed for radioanalytical chemistry measurements as part of MARLAP Chapters 19–20 (NRC 2004). MARSSIM, draft Revision 2, provides guidance for developing MQOs as an important subset of inputs into the DQO process, which defines performance requirements and objectives for the measurement system. MQOs that should be considered include the following: method uncertainty, detection capability, range, specificity, and ruggedness (NRC 2020b). These concepts apply to both laboratory and field measurements of radiation and radioactivity and both MARSAME and MARSSIM, draft Revision 2, incorporate these ideas and extend them to these measurements.

KEY POINTS

- Essential guidance for measurement uncertainty calculations is contained in the document generally known as the **ISO GUM** (ISO IEC GUIDE 98-3 2008(E), "Uncertainty of Measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)" (ISO 2008a) https://isotc.iso.org/livelink/livelink/Open/8389141
- Applications and examples for radiological analytical chemistry measurements are given in MARLAP, Volume III, Chapter 19.
- These concepts apply equally well to field measurements of radiation and radioactivity. The MARSAME process incorporates these ideas and extends them to these measurements (MARSAME, Chapter 7).
- Software programs are available to perform the calculations needed to determine the combined standard uncertainty of a measurement including GUMCalc, the National Institute of Standards and Technology (NIST) Uncertainty Machine, and the commercial software package GUM Workbench Version 1.4.
- An example uncertainty calculation using GUMCalc is provided to contrast the difficulty with that of a hand calculation approach, showing why use of software such as GUMCalc is highly recommended.

This section summarizes the current recommendations on measurement uncertainty from NIST, the ISO GUM (ISO 2008a), MARSAME Chapter 7, and from MARLAP Chapters 19 and 20.

12.1 REPORTING SURVEY RESULTS

In MARSSIM, draft Revision 2, the NRC has published standard guidance on the reporting of survey results that includes uncertainty. This guidance is summarized as follows:

- Even negative results and results with large uncertainties can be used in the statistical tests to demonstrate compliance. Results reported only as "< MDC" cannot be fully used and, for example, complicate even such simple analyses as an average. Although the nonparametric tests and the upper confidence limit comparison can accommodate situations where up to 40 percent of the results are "non-detects," it is better to report the actual results.

- Report results using the correct units and the correct number of significant digits. The choice of reporting results using International System units (e.g., Bq/kg, Bq/m^2) or conventional units (e.g., pCi/g, dpm/100 cm^2) is made on a site-specific basis. Generally, MARSSIM recommends that all results be reported in the same units as the DCGLs. Sometimes the results may be more convenient to work with as counts directly from the detector. In these cases, the user should decide on the appropriate units for a specific survey based on the survey objectives. MARLAP suggests that the uncertainty and MDC should be reported to two significant figures, while environmental radiation measurements seldom warrant more than two or three significant figures.

- Report the measurement uncertainty for every analytical result or series of results, such as for a measurement system. This uncertainty, while not directly used for demonstrating compliance with the release criteria, is applied in survey planning and data assessment throughout the RSSI process. In addition, the uncertainty is used for evaluating the performance of measurement systems using QC measurement results (for scans and direct measurements and for laboratory analysis of samples). The uncertainty is also used for comparing individual measurements to the AL, which is especially important in the early stages of the RSSI process (scoping, characterization, and remedial action support surveys) when decisions are made based on a limited number of measurements.

Section 6.4 of MARSSIM, draft Revision 2, discusses methods for calculating the measurement uncertainty and addresses systematic and random uncertainties, statistical counting uncertainty, uncertainty propagation, and reporting confidence intervals. The remainder of this section expands the material in MARSSIM, draft Revision 2, and incorporates the guidance to the expression of uncertainty in measurement from the ISO GUM. Note that the GUM terminology and references do not appear in MARSSIM, draft Revision 2, and are presented in this white paper with reference to software that aids the calculations for field applications. This white paper contains certain ISO and MARLAP recommendations to determine uncertainty for both laboratory and field measurements.

12.2 UNCERTAINTY

The ISO GUM guidance is contained in a series of documents, the most important of which is ISO IEC GUIDE 98-3 (ISO 1995):

- ISO IEC GUIDE 98-1, "Uncertainty of measurement—Part 1: Introduction to the expression of uncertainty in measurement," issued in 2009 (ISO 2009)
- ISO IEC GUIDE 98-3 2008(E), "Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)," First Edition, issued in 2008 (ISO 2008a)
- ISO IEC GUIDE 98-4, "Uncertainty of measurement—Part 4: Role of measurement uncertainty in conformity assessment," First Edition, issued in 2012 (ISO 2012)
- ISO IEC GUIDE 98-3/Suppl.1, "Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), Supplement 1: Propagation of distributions using a Monte Carlo method," issued in 2008 (ISO 2008b)
- ISO IEC GUIDE 98-3/Suppl.2, "Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), Supplement 2: Extension to any number of output quantities," issued in 2011 (ISO 2011)

The above references can be downloaded at https://isotc.iso.org/livelink/livelink/Open/8389141 and at https://www.bipm.org/en/publications/guides/gum.html.

An excellent introduction to the ISO GUM appears in NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," issued September 1994 (NIST 1994).

MARLAP Volume III, Chapter 19, "Measurement Uncertainty," discusses the evaluation and reporting of measurement uncertainty in radiological analytical chemistry measurements. Laboratory measurements always involve uncertainty, which must be considered when analytical results are used in making decisions.

MARLAP Volume III, Chapter 20, "Detection and Quantification Capabilities," discusses issues related to analyte detection and quantification capabilities.

MARLAP recommends the following:

- For evaluating and reporting measurement uncertainty, adopt the terminology and methods of the ISO GUM (ISO 2008a)
- The laboratory QC procedures should be used to ensure the measurement process remains in a state of statistical control.
- Uncertainty estimates should account for both random and systematic effects in the measurement process, but they should not account for possible blunders or other spurious errors. Spurious errors indicate a loss of statistical control of the process.
- Each measured value should be reported with either its combined standard uncertainty (or its expanded uncertainty).

- Reported measurement uncertainties should be clearly explained. (When an expanded uncertainty is reported, the coverage factor should be stated along with the approximate coverage probability.)

- All potentially significant sources of measurement uncertainty should be considered and, for each source, the uncertainties evaluated and propagated through to the final result.

- Each uncertainty should be rounded to either one or two significant figures, and the measured value should be rounded to the same number of decimal places as its uncertainty. (MARLAP prefers the use of two figures in the uncertainty.) Only final results should be rounded in this manner.

- All results, whether positive, negative, or zero, should be reported as obtained, together with their uncertainties.

The usual steps for evaluating and reporting the uncertainty of a measurement may be summarized as follows (adapted from Chapter 8 of the GUM):

(1) Identify the measurand, Y, and all the input quantities, X_i, for the mathematical model. Include all quantities whose variability or uncertainty could have a potentially significant effect on the result. Express the mathematical relationship, $Y = f(X_1,X_2,.,X_N)$, between the measurand and the input quantities. This is sometimes called the model equation. This step can be somewhat daunting, but should be started with the model equation used to convert the measured value (e.g., count or count rate) to the desired final result (e.g., activity concentration).

(2) Determine an estimate, x_i, of the value of each input quantity, X_i. This should be the value that would normally be used to calculate the final result.

(3) Evaluate the standard uncertainty, $u(x_i)$, for each input estimate, x_i. This is the uncertainty expressed as an estimated standard deviation. These are of two types: Type A, which is uncertainties evaluated by the statistical analysis of a series of observations, or Type B, which is uncertainties evaluated by any other method.

For example, the sample standard deviation is a Type A estimate of the population standard deviation. The square root of the observed counts is a Type B estimate of the population standard deviation because it depends on the assumption of a Poisson distribution for the counting uncertainty in a single gross radiation counting measurement.

(4) Evaluate the covariances, $u(x_i,x_j)$, for all pairs of input estimates with potentially significant correlations. If the input quantities are independent, then these covariances are zero.

(5) Calculate the estimate, y, of the measurand from the relationship $y = f(x_1, x_2,.,x_N)$, where f is the function determined in step 1.

(6) Determine the combined standard uncertainty, $u_c(y)$, of the estimate, y. The combined uncertainty in the estimate, $y = f(x_1, x_2,.,x_N)$, can be estimated using the familiar law of propagation of uncertainty:

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)$$

where $u_c^2(y)$ is the square of the combined standard uncertainty and the $\left(\frac{\partial f}{\partial x_i} \right)$ are called sensitivity coefficients. Note that this method is based on a first-order (linear) Taylor series approximation to the model function, $Y = f(X_1, X_2, ., X_N)$. (If Y is highly nonlinear, more terms of the Taylor series expansion may be needed.) In practice, this tends not to be a problem. Comparison of results using the approximation usually agree well with other methods (i.e., Monte Carlo.) This should not be too surprising since most measurement devices are designed to operate over a region of values of the input parameters that results in a linear response of the output quantity of interest.

If the covariances, $u(xi,xj)$, for all pairs of input estimates are zero, this simplifies to:

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)$$

The partial derivative with respect to x can be approximated by looking at the change in $f(x_i)$ when there is a very small change in x_i . This is why these partial derivatives are called sensitivity coefficients.

(7) Optionally multiply $u_c(y)$ by a coverage factor k to obtain the expanded uncertainty U such that the interval $[y - U, y + U]$ can be expected to contain the value of the measurand with a specified probability.

(8) Report the result as $y \pm U$ with the unit of measurement, and at a minimum, state the coverage factor used to compute U and the estimated coverage probability. Alternatively, report the result, y, and its combined standard uncertainty, $u_c(y)$, with the unit of measurement.

MARLAP contains examples of these calculations.

Software programs are available to perform the calculations needed to determine the combined standard uncertainty of a measurement. GUMCalc is a free Windows[TM] program written by the major contributor to Chapters 19 and 20 of MARLAP, who is also the Chief Metrologist at the EPA's National Analytical Radiation Environmental Laboratory in Montgomery, Alabama. The program is available at http://mccroan.com/gumcalc.html. Unlike most programs of this type, GUMCalc computes the exact partial derivatives needed to obtain the sensitivity coefficients rather than the approximate method mentioned in step 6 above. In addition to its ability to propagate measurement uncertainty automatically, GUMCalc also has the unusual ability to propagate the dimensions of measurable quantities making it a measurement modeling tool rather than simply a calculator program. (It can also be used without a model for unit conversions.) SC&A has found this program extremely easy to use, and it has been informally tested successfully against other calculations. It has not had the publicity of some other uncertainty calculation software and has not been independently verified and validated. Section 11.5 shows how the GUMCalc software can be used to calculate the standard uncertainty, relieving the user from having to compute partial derivatives and the tedious calculations that are involved in evaluating them.

The NIST Uncertainty Machine is a Web-based software application to evaluate the measurement uncertainty associated with an output quantity defined by a measurement model of the form $y = f(x_1, x_2,..,x_N)$. It is available at https://uncertainty.nist.gov/. The NIST Uncertainty Machine implements the approximate method of uncertainty evaluation described in GUM and the Monte Carlo method in GUM Supplements 1 and 2. Input and output quantities are modeled as random variables, and their probability distributions are used to characterize measurement uncertainty. The Monte Carlo method avoids the linear approximation of the original GUM. For inputs that are correlated, the NIST Uncertainty Machine offers the means to specify the corresponding correlations and the manner in which they will be considered. The user's manual is available at https://uncertainty.nist.gov/NISTUncertaintyMachine-UserManual.pdf. The computational engine of the NIST Uncertainty Machine is written in the R language for statistical computing and graphics (free; see https://www.r-project.org/).

The commercial software package GUM Workbench Version 1.4 (1700 EUR) is a basic tool for the evaluation of uncertainty in measurement with one result quantity and one budget table. The calculation can be done using uncertainty propagation (following GUM) or using Monte Carlo simulation (following GUM Supplement 1). A more advanced Version 2.4 (2700 EUR) is available for the evaluation of uncertainty in measurement with multiple result quantities and multiple budget tables. There are demonstration and educational versions available for download at http://www.metrodata.de/download_en.html.

Many other software tools are available, many free, for aiding in the calculation of measurement uncertainty. Most have not been subjected to external verification and validation and often do not work (caveat emptor).

12.3 DETECTION DECISIONS

Chapter 20 of MARLAP makes recommendations concerning detection decisions based on measurements. These recommendations are framed in the context of a laboratory measurement of a sample, but apply equally well to direct measurements under specified conditions at a specific location in the field. The MARSAME manual, which provides technical information on survey approaches to determine proper disposition of materials and equipment, discusses these issues in greater detail. (MARSAME is a supplement to MARSSIM.)

When a detection decision is required, it should be made by comparing the gross signal, net signal, or measured concentration to its corresponding critical value.

The laboratory should choose expressions for the critical value and minimum detectable value that are appropriate for the structure and statistics of the measurement process. The desired Type I and Type II error rates (both 5 percent by default) may be specified but should not require particular equations for the critical value or the minimum detectable value without detailed knowledge of the measurement process.

An appropriate radiochemical blank should be used to predict the signal produced by a sample that contains no analyte. The most appropriate type of blank for this purpose depends on the analyte and on the method and conditions of measurement. Depending on the circumstances, it may be a blank source, reagent blank, or other process blank that accounts for instrument background, as well as any contaminants introduced during the processing of the sample. For field measurements, an appropriate reference background should be obtained.

The validity of the Poisson approximation for the measurement process should be assessed before using an expression for the critical value that is based on Poisson statistics.

When the analyte is present at observable levels in the water, reagents, and labware used in the analysis, the Poisson approximation is often inappropriate. In these cases, *replicated blanks* may be employed to calculate the standard uncertainty used to determine the critical value.

All sources of uncertainty should be considered in the instrument signal (or other response variable) when calculating the critical value and minimum detectable value. This echoes the recommendation in MARLAP, Chapter 19, that all potentially significant sources of measurement uncertainty should be considered, and for each, the uncertainties should be evaluated and propagated through to the final result.

The minimum detectable value (MDC or the minimum detectable activity (MDA)) should be used only as a performance characteristic of the measurement process. A measurement result should never be compared to the minimum detectable value to make a detection decision.

Each measurement result and its uncertainty should be reported as obtained (as recommended in Chapter 19) even if the result is less than zero. The laboratory should *never* report a result as less than an MDC.

The minimum detectable value should not be used for projects where the issue is quantification of the contaminant of concern and not just detection. For these projects, MARLAP recommends the minimum quantifiable value as a more relevant performance characteristic of the measurement process. The *minimum quantifiable concentration*, or the *minimum quantifiable value* of the concentration, is defined as the smallest concentration that ensures that the relative *standard deviation* of the measurement does not exceed a specified value, usually 10 percent.)

12.4 SUBSAMPLING

Laboratories routinely receive larger samples than required for analysis. The challenge then becomes to prepare a sample that is representative and large enough for analysis, but not so large as to cause needless work in its final preparation. Generally, a raw sample is first crushed to a reasonable particle size, and a portion of the crushed material is taken for analysis. Section 12.3.1.4 of MARLAP discusses subsampling.

French geologist Pierre Gy (1992) has developed a theory of particulate sampling that applies to subsampling in the laboratory. Appendix F to MARLAP, Volume 2, summarizes important aspects of the theory and includes applications to radiochemistry. Important points to remember include the following:

- For most practical purposes, a subsample is guaranteed to be unbiased only if every particle in the sample has the same probability of being selected for the subsample.
- The weight of the subsample should be many times greater than the weight of the largest particle in the sample.
- The variance associated with subsampling may be reduced either by increasing the size of the subsample or by reducing the particle sizes before subsampling.
- Grouping and segregation of particles tend to increase the subsampling variance.
- Grouping and segregation can be reduced by increment sampling, splitting, or mixing.

Pierre Gy's theory defines the *fundamental error* as the minimum subsampling error that depends on the composition, shape, fragment size distribution, and chemical properties of the material; it is not affected by homogenization or mixing. It arises when the analyte of interest is concentrated in constituent "nuggets" or "hot particles." As a conceptual example of fundamental error, consider a large container filled mostly with "clean" soil particles into which a few hot particles have been mixed well. If a small subsample is taken, it is possible, and even likely, that no hot particles would be selected as part of the subsample. This would lead to a major underestimate of the concentration of residual radioactivity. With a small subsample, it is also possible that a gross overestimate of the concentration of residual radioactivity will occur if one or more hot particles is included in the subsample, because these particles may account for a disproportionately large amount of residual radioactivity for the size of the subsample.

12.5 UNCERTAINTY CALCULATION USING GUMCALC

Example 19.9 taken from MARLAP, pages 19-21 to 19-24, will be used to show how the GUMCalc software can be utilized to calculate the standard uncertainty, relieving the user of having to compute partial derivatives and the tedious calculations that are involved with evaluating them. This example appears here because a step-by-step illustration of this process does not seem to be available.

Problem: A 6000-second gross-alpha measurement is performed on a test source prepared by evaporating water on a stainless steel planchet. The measurement produces 120 alpha counts. The preceding blank measurement on the instrument had a duration of 6000 s and produced 42 alpha counts. The estimated alpha-particle counting efficiency is 0.223 with a standard uncertainty of 0.015. The sample volume analyzed is 0.05000 L, with a standard uncertainty of 0.00019 L. The alpha-particle emission rate per unit volume is described by the mathematical model

$$c_\alpha = \frac{N_S / t_S - N_B / t_B}{\varepsilon V}$$

where

c_α	is the alpha-particle emission rate per unit volume;
N_S	is the source count ($N_S = 120$);
N_B	is the blank count ($N_B = 42$);
t_S	is the source count time ($t_S = 6000$ s);
t_B	is the blank count time ($t_B = 6000$ s);
ε	is the counting efficiency ($\varepsilon = 0.223$); and
V	is the volume analyzed ($V = 0.0500$ L).

What is the output estimate c_α and what is its combined standard uncertainty, $u_c(c_\alpha)$? (Use the Poisson approximation for the uncertainties of N_S and N_B.)

Solution: First compute the output estimate c_α (alpha particles per second per liter).

$$c_\alpha = \frac{N_S / t_S - N_B / t_B}{\varepsilon V} = \frac{120/6000 - 42/6000}{(0.223)(0.05000)} \approx 1.17 \text{ s}^{-1} \cdot \text{L}^{-1}$$

Then compute the combined standard uncertainty $u_c(c_\alpha)$. The only uncertainties included in the model will be those associated with the counts N_S and N_B, the efficiency ε, and the volume V. There is no reason to suspect correlations between the measured values; so, the uncertainty propagation formula becomes

$$u_c^2(c_\alpha) = \left(\frac{\partial c_\alpha}{\partial N_S}\right)^2 u^2(N_S) + \left(\frac{\partial c_\alpha}{\partial N_B}\right)^2 u^2(N_B) + \left(\frac{\partial c_\alpha}{\partial \varepsilon}\right)^2 u^2(\varepsilon) + \left(\frac{\partial c_\alpha}{\partial V}\right)^2 u^2(V)$$

The sensitivity coefficients are evaluated using the differentiation rules shown in Table 19.1:

$$\begin{aligned}\frac{\partial c_\alpha}{\partial N_S} &= \frac{\partial(N_S / t_S - N_B / t_B) / \partial N_S}{\varepsilon V} \\ &= \frac{\partial(N_S / t_S) / \partial N_S - 0}{\varepsilon V} \\ &= \frac{\partial N_S / \partial N_S}{t_S \varepsilon V} \\ &= \frac{1}{t_S \varepsilon V} \\ &= 0.0149477 \text{ s}^{-1} \cdot \text{L}^{-1}\end{aligned}$$

$$\begin{aligned}\frac{\partial c_\alpha}{\partial N_B} &= \frac{\partial(N_S / t_S - N_B / t_B) / \partial N_B}{\varepsilon V} \\ &= \frac{0 - \partial(N_B / t_B) / \partial N_B}{\varepsilon V} \\ &= \frac{-\partial N_B / \partial N_B}{t_B \varepsilon V} \\ &= \frac{-1}{t_B \varepsilon V} \\ &= -0.0149477 \text{ s}^{-1} \cdot \text{L}^{-1}\end{aligned}$$

$$\begin{aligned}\frac{\partial c_\alpha}{\partial \varepsilon} &= -\frac{N_S / t_S - N_B / t_B}{\varepsilon^2 V} \frac{\partial \varepsilon}{\partial \varepsilon} \\ &= -\frac{N_S / t_S - N_B / t_B}{\varepsilon^2 V} \\ &= -5.22834 \text{ s}^{-1} \cdot \text{L}^{-1}\end{aligned}$$

$$\begin{aligned}\frac{\partial c_\alpha}{\partial V} &= -\frac{N_S / t_S - N_B / t_B}{\varepsilon V^2} \frac{\partial V}{\partial V} \\ &= -\frac{N_S / t_S - N_B / t_B}{\varepsilon V^2} \\ &= -23.3184 \text{ s}^{-1} \cdot \text{L}^{-2}\end{aligned}$$

The Poisson approximation is used for the standard uncertainties of the counts N_S and N_B. So,

$$u^2(N_S) = N_S = 120 \quad \text{and} \quad u^2(N_B) = N_B = 42$$

Recall from the statement of the problem that $u(\varepsilon) = 0.015$ and $u(V) = 0.00019$. When the values of all these expressions are substituted into the uncertainty propagation formula, the combined variance is

$$\begin{aligned} u_c^2(c_\alpha) &= (0.0149477)^2(120) + (-0.0149477)^2(42) + (-5.22834)^2(0.015)^2 \\ &\qquad + (-23.3184)^2(0.00019)^2 \\ &= 0.0424 \ \mathrm{s}^{-2} \cdot \mathrm{L}^{-2} \end{aligned}$$

So, the combined standard uncertainty is $u_c(c_\alpha) = \sqrt{0.0424} \approx 0.21 \ \mathrm{s}^{-1} \cdot \mathrm{L}^{-1}$.

In contrast to the hand calculations for the above equations, GUMCalc Version 0.99.10, dated May 25, 2019, and downloadable at http://mccroan.com/gumcalc.html, can be used in a much simpler fashion, as the following shows:

1. **Start the GUMCalc Software and Figure 12-1 appears.**

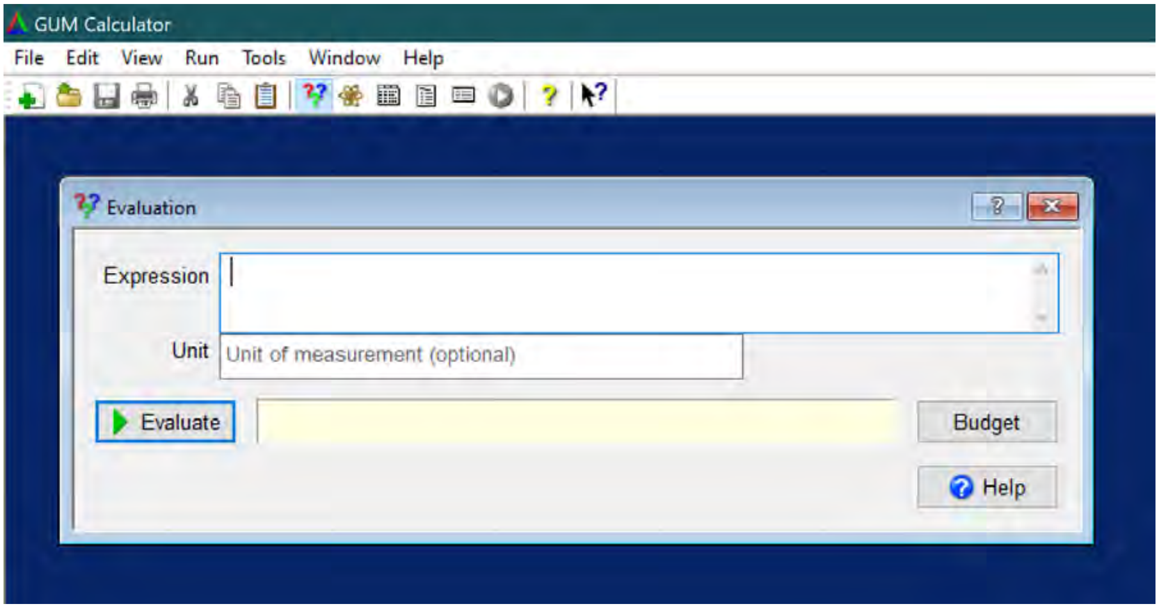

Figure 12-1 GUMCalc Initial Screen

Source: GUMCalc (http://mccroan.com/gumcalc.html)

2. **Select File New: and Figure 12-2 appears.**

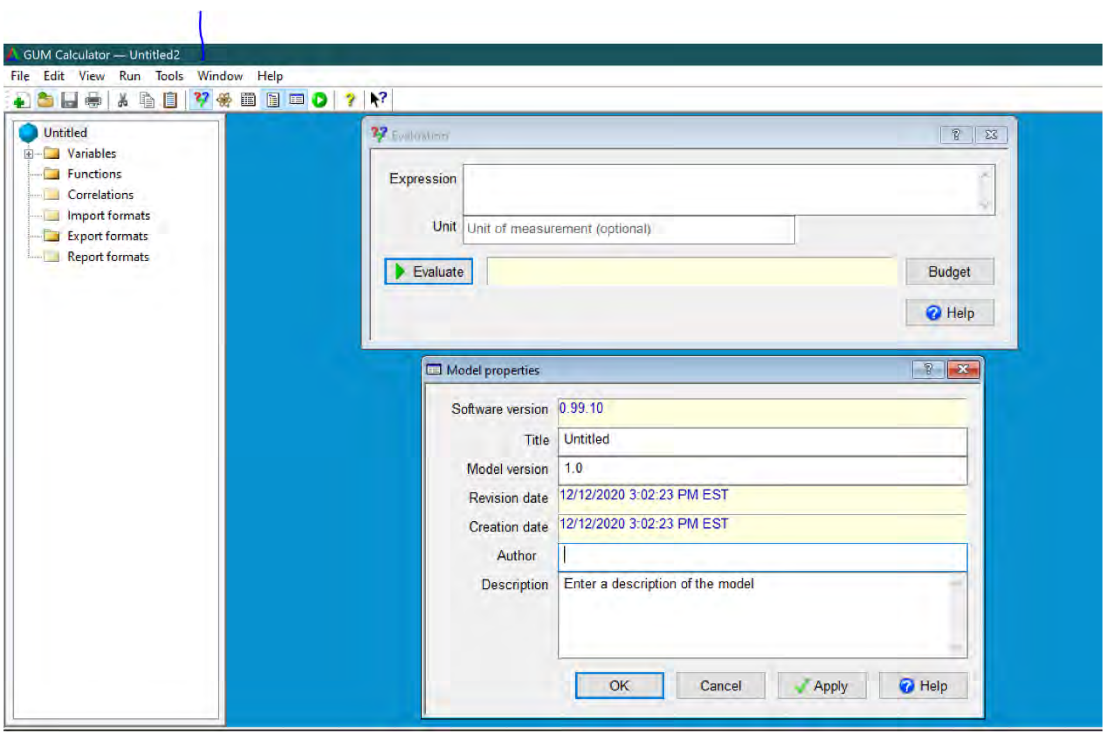

Figure 12-2 GUMCalc Open File New Screen

Source: GUMCalc (http://mccroan.com/gumcalc.html)

3. Fill out the model properties (Figure 12-3) and Select Apply and then OK.

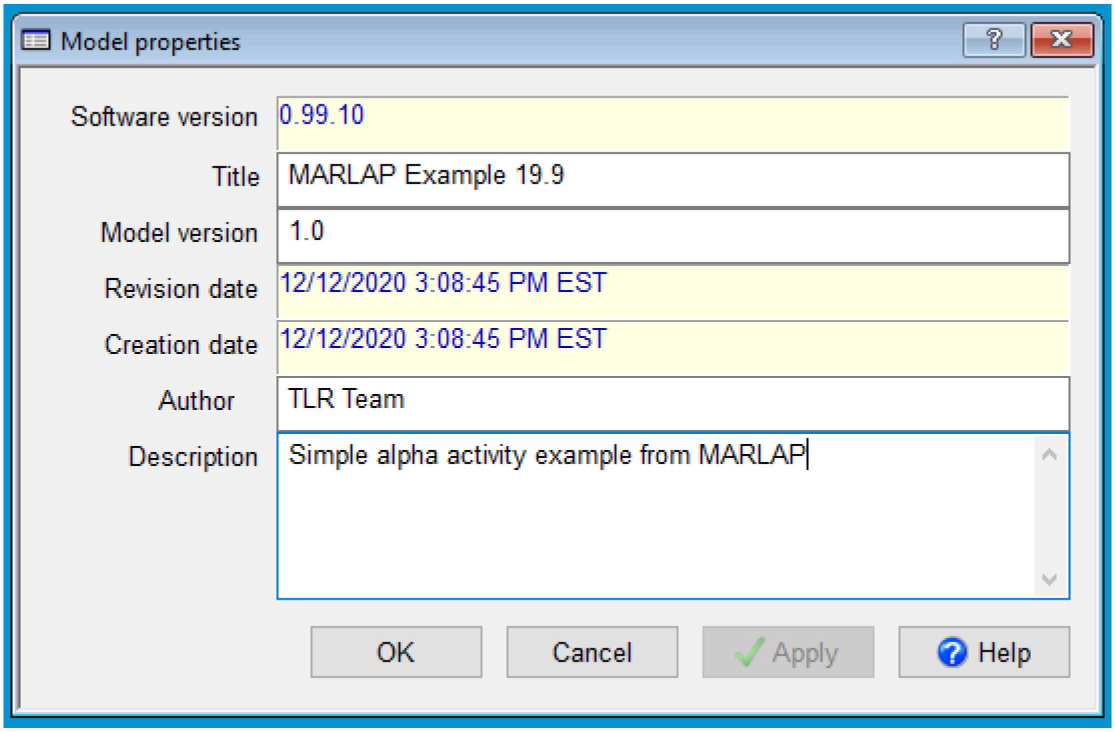

Figure 12-3 GUMCalc Model Properties Screen

Source: GUMCalc (http://mccroan.com/gumcalc.html)

Expressions are entered with a syntax similar to that used in many computer programming languages. Next, the input variables are entered. Note that in older versions of GUMCalc some of the features described in the help file have changed (the Definitions window no longer appears automatically when a new .gum file is opened). The default view of an open model is now a "tree view," but the Definitions window can be opened by pressing F7.

4. Right click on Input and Figure 12-4 appears; Select New.

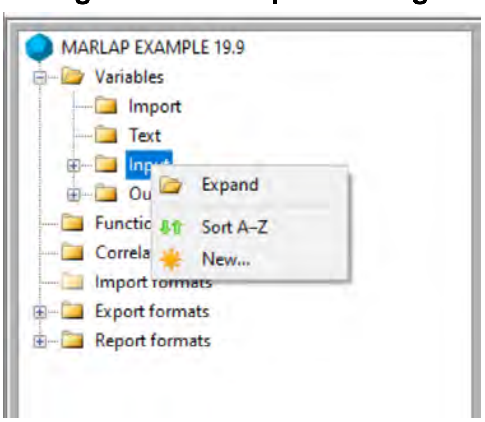

Figure 12-4 GUMCalc Input Screen

Source: GUMCalc (http://mccroan.com/gumcalc.html)

5. Complete new variables as shown in Figures 12-5 through 12-10.

The variables sample counts, background counts, sample count time, background count time, efficiency, and volume (values and the distribution) are entered using the information available from the measurement. These input variables can be given names that will be easy to interpret. Naming rules followed by common programming languages are generally accepted. **These input variables must be entered before output variables.** For the sample counts, the result was 120, with no units since it is a count, and the distribution is assumed to be Poisson:

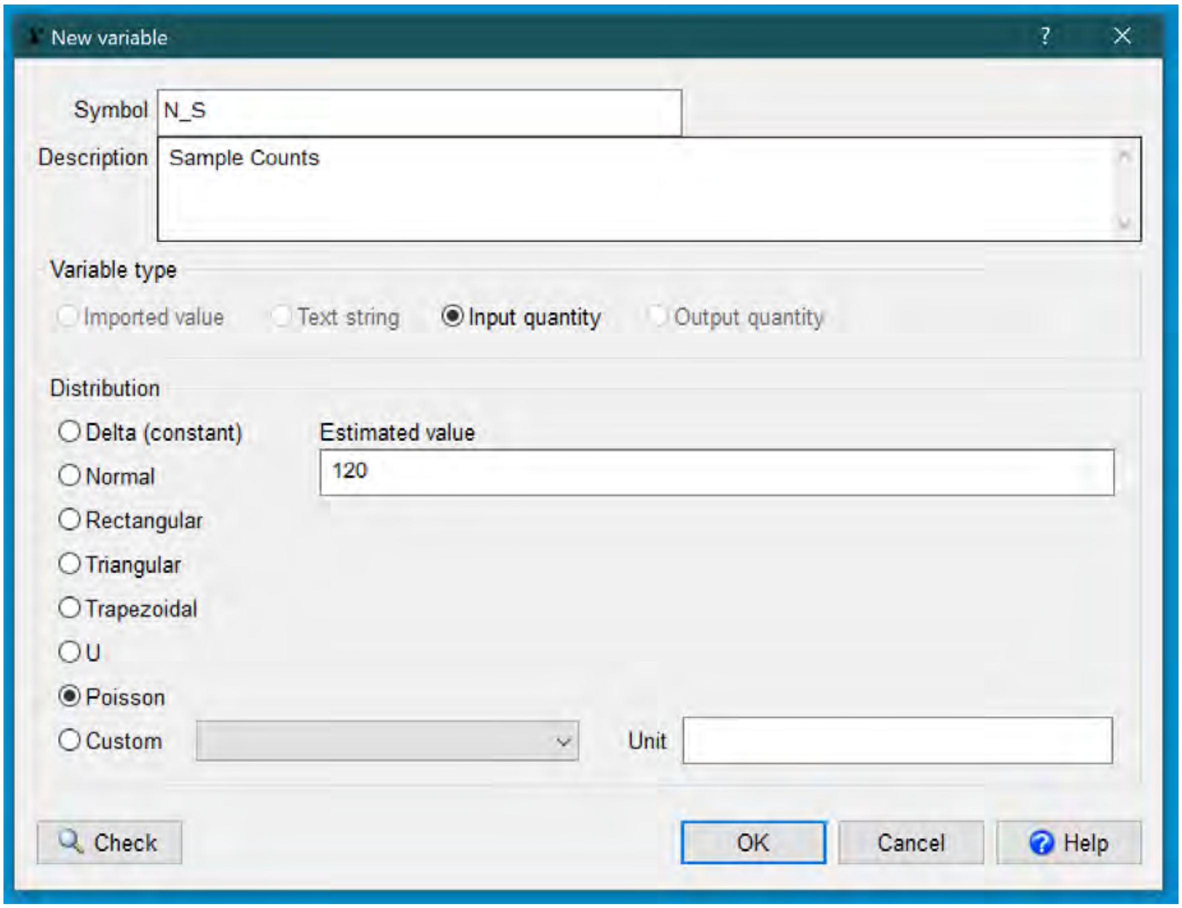

Figure 12-5 GUMCalc Input Screen for Sample Counts

Source: GUMCalc (http://mccroan.com/gumcalc.html)

The other input quantities are created and entered in a similar manner:

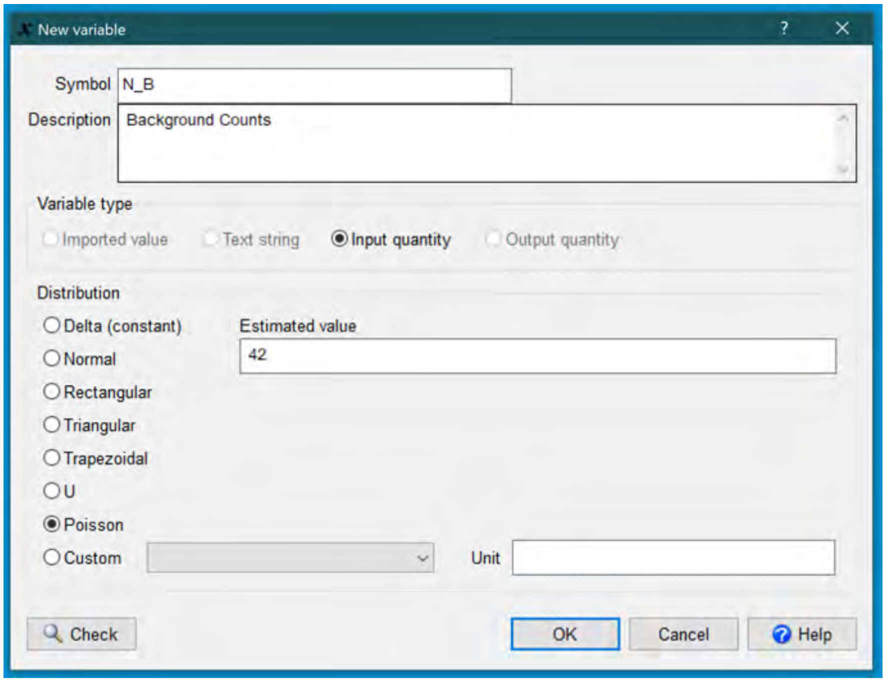

Figure 12-6 GUMCalc Input Screen for Background Counts

Source: GUMCalc (http://mccroan.com/gumcalc.html)

Constants are entered as having a delta distribution; namely, the probability of the estimated value is 1, and the probability of anything else is 0.

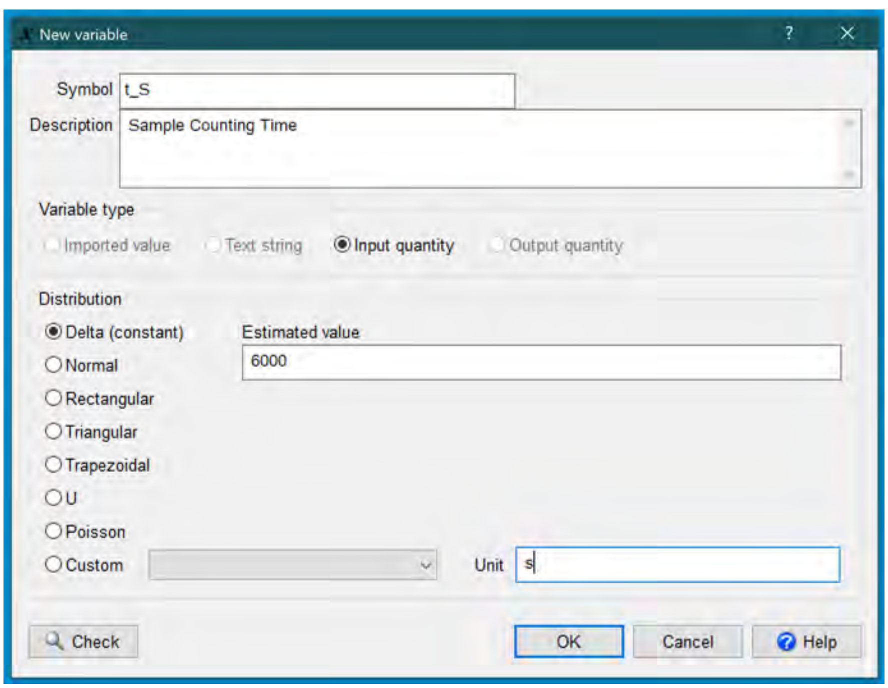

Figure 12-7 GUMCalc Input Screen for Sample Count Time

Source: GUMCalc (http://mccroan.com/gumcalc.html)

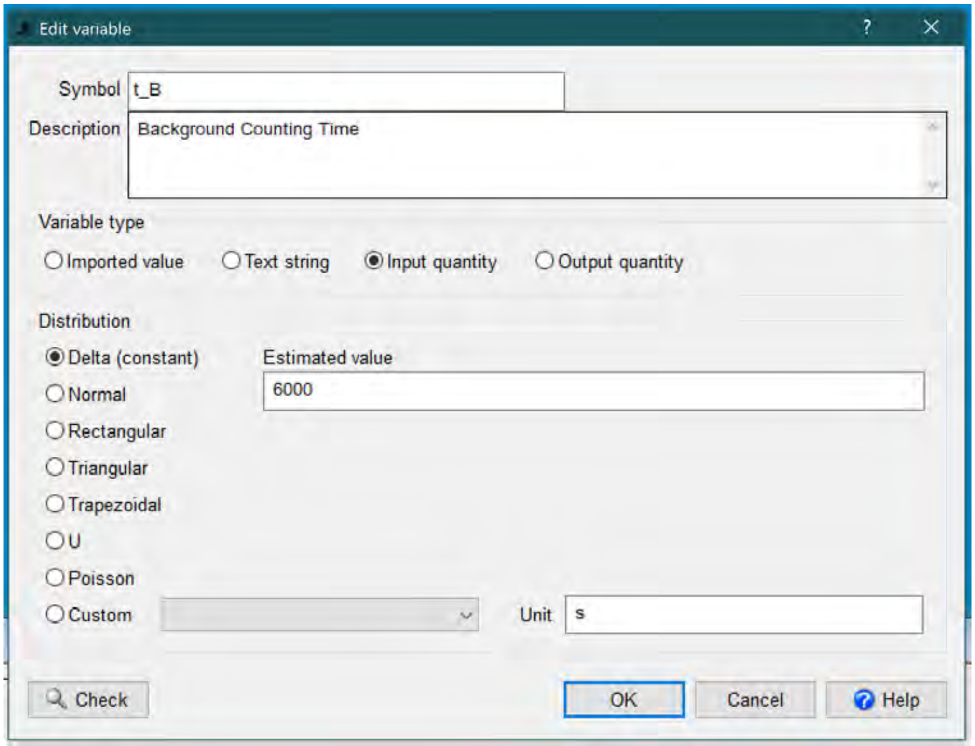

Figure 12-8 GUMCalc Input Screen for Background Count Time

Source: GUMCalc (http://mccroan.com/gumcalc.html)

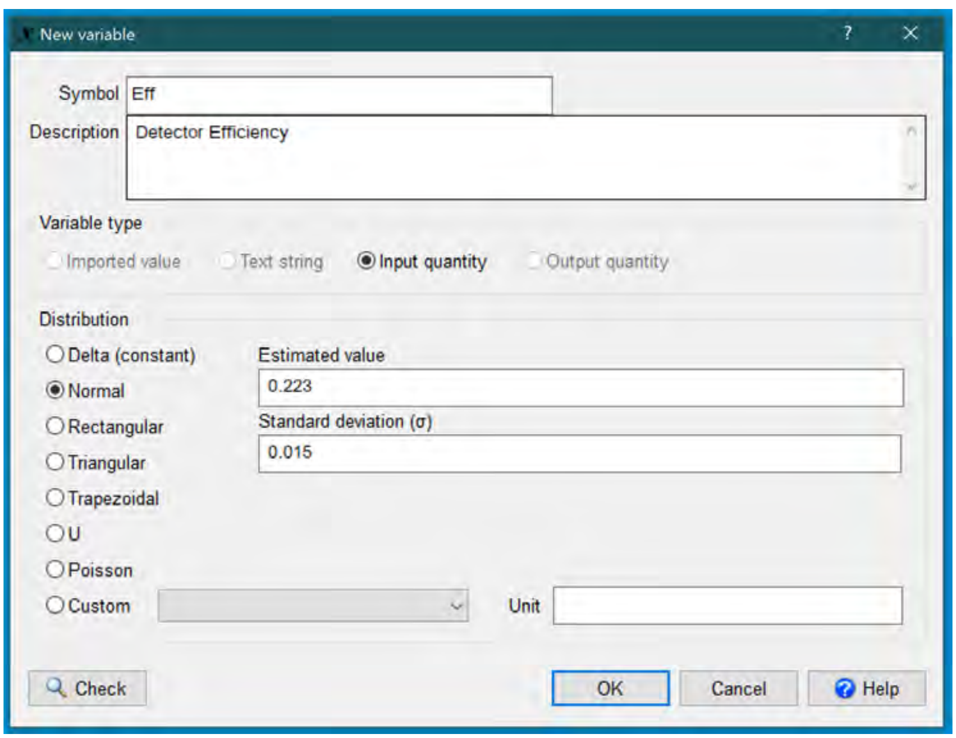

Figure 12-9 GUMCalc Input Screen for Detector Efficiency

Source: GUMCalc (http://mccroan.com/gumcalc.html)

Any volumetric measuring device should have a specified tolerance for its capacity, or for the possible bias of the device. This tolerance may be assumed to represent the half-width of a rectangular or triangular distribution.

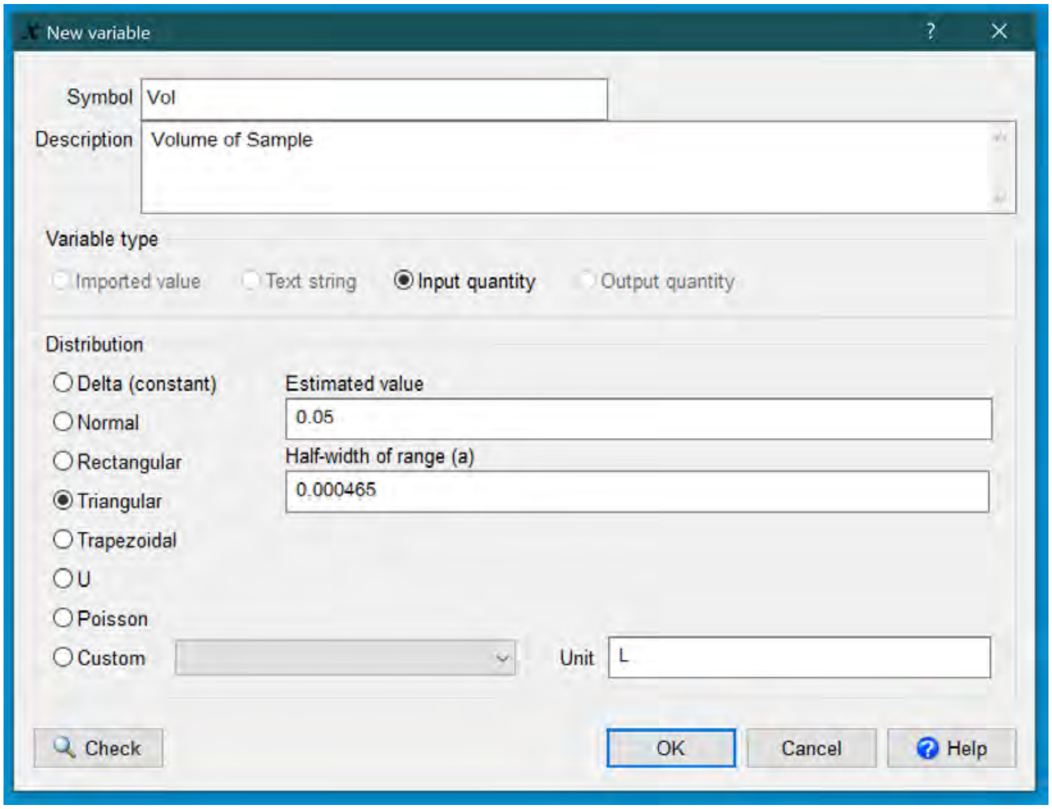

Figure 12-10 GUMCalc Input Screen for Sample Volume

Source: GUMCalc (http://mccroan.com/gumcalc.html)

6. Select Variables-Output-New as shown in Figure 12-11.

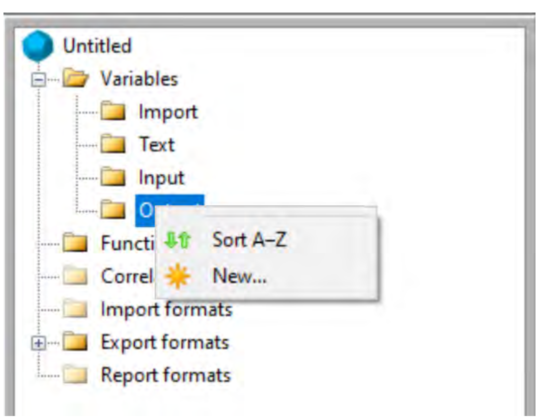

Figure 12-11 GUMCalc Screen for Output Selection

Source: GUMCalc (http://mccroan.com/gumcalc.html)

7. Enter data for output including formula and unit and click OK.

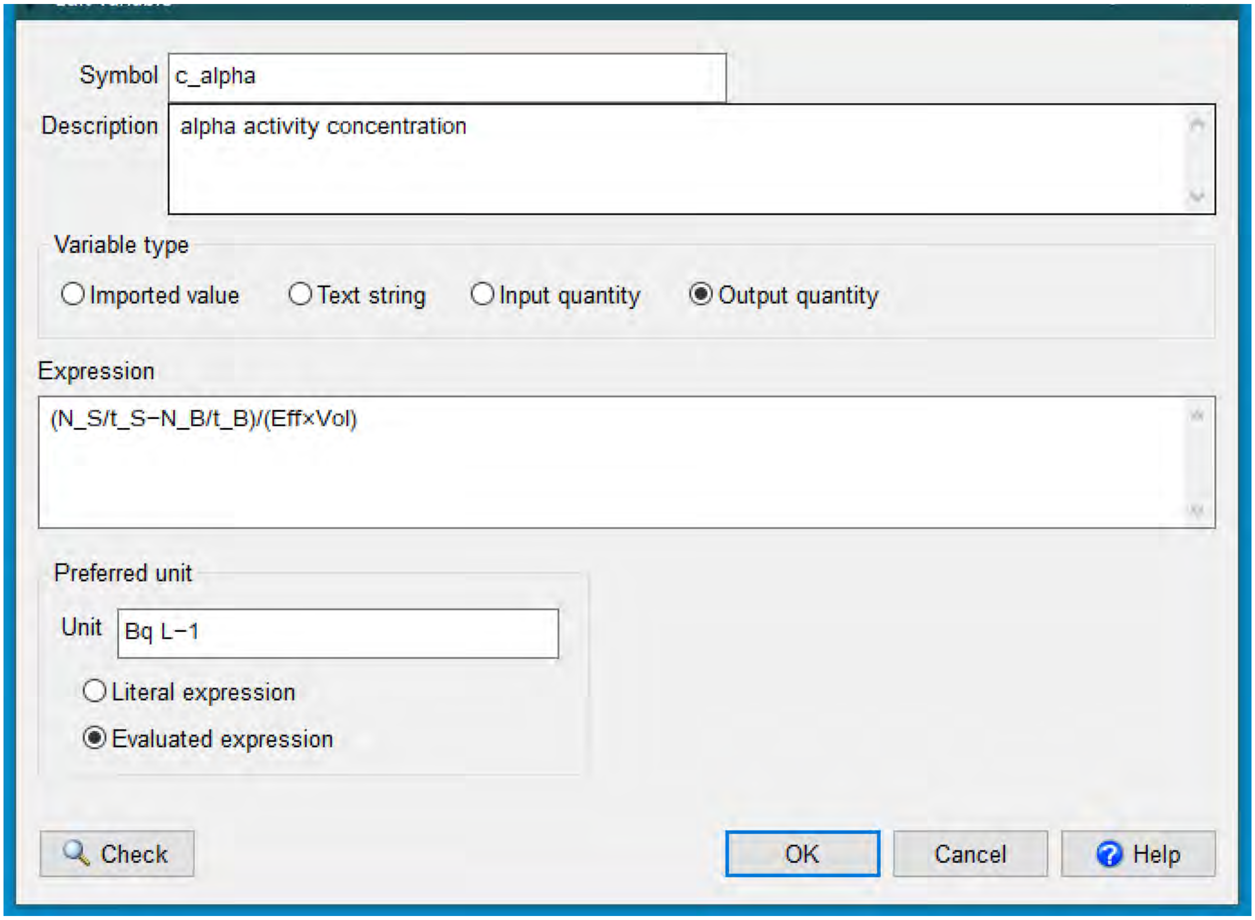

Figure 12-12 GUMCalc Screen for Output with Formula and Units

Source: GUMCalc (http://mccroan.com/gumcalc.html)

8. Select View—Evaluation Window.

In the evaluation dialog, the expression to be evaluated is entered. In this case. it is simply the output quantity c_alpha. When "Evaluate" is clicked, the answer appears with the standard uncertainty (one sigma) rounded to two significant figures and the result rounded to match.

As shown in Figure 12-13, for this case 1.17 Bq/L ± 0.21, the preferred units specified for the output quantity are used. The expression "c_alpha" may be selected or typed in. The input variables and symbols are shown on the screen.

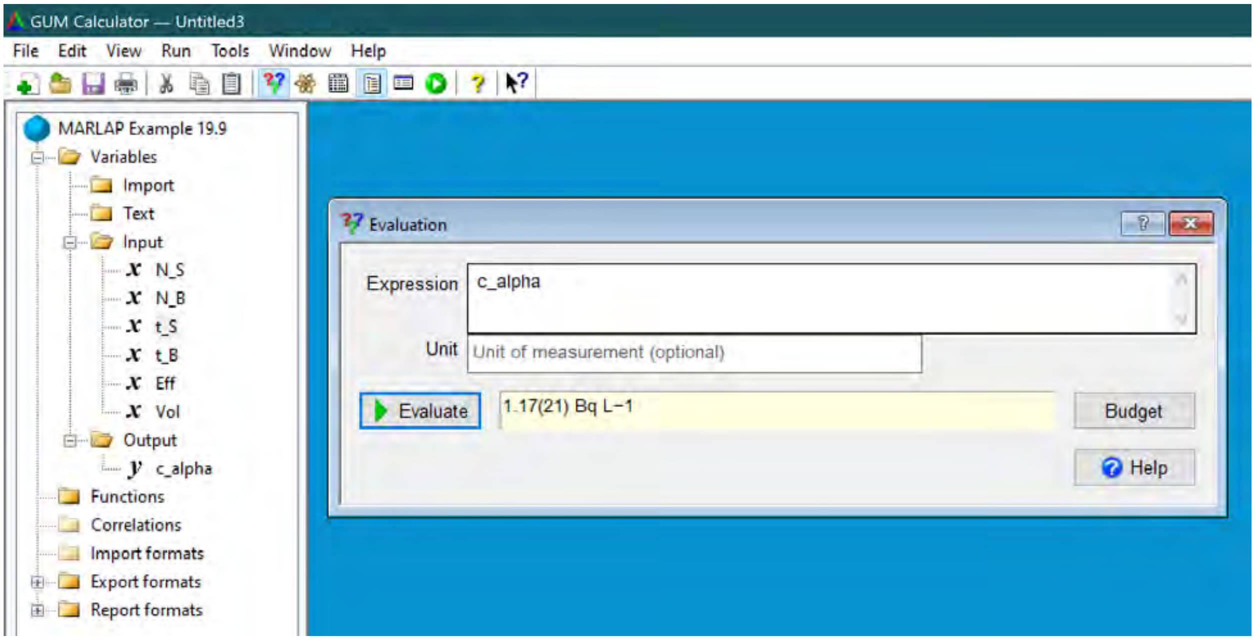

Figure 12-13 GUMCalc Evaluation Output Screen

Source: GUMCalc (http://mccroan.com/gumcalc.html)

If the units are changed, the expression will be given in those units—namely, 31.5 pCi/L ± 5.6, as shown in Figure 12-14.

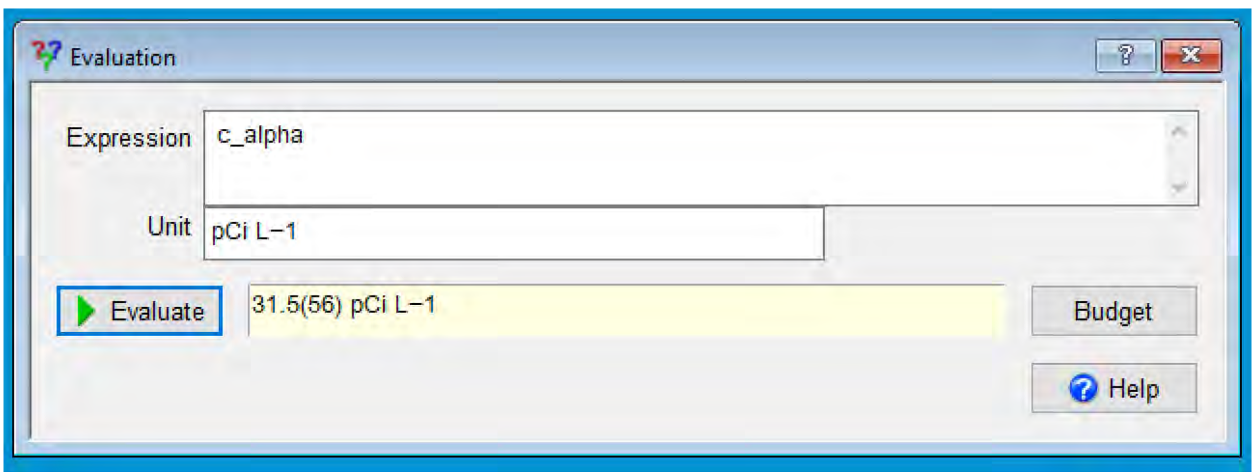

Figure 12-14 GUMCalc Evaluation Screen with Other Units

Source: GUMCalc (http://mccroan.com/gumcalc.html)

The Evaluation dialog can be used as a calculator and for unit conversion without having to specify a measurement model.

9. When the Budget button is clicked, the uncertainty budget for this measurement is shown as in Figure 12-15.

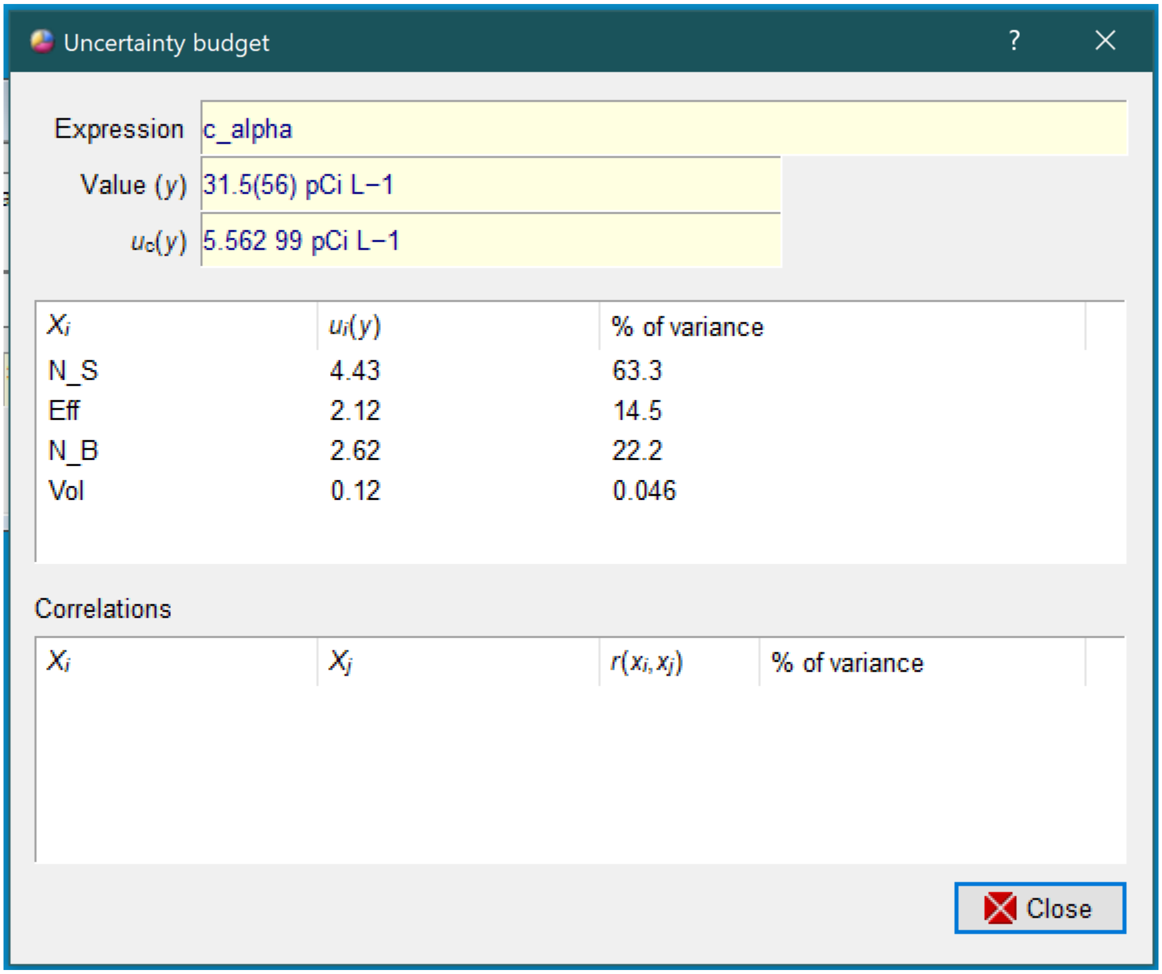

Figure 12-15 GUMCalc Uncertainty Budget Screen

Source: GUMCalc (http://mccroan.com/gumcalc.html)

The uncertainty budget shows which input quantity is contributing the most to the variance of the measurement. In this case, it is the sample counts followed by the background counts, so the best way to decrease the uncertainty is increase the counting time. This may be obvious in this case, but it shows the principle of having an uncertainty budget.

13 ELEVATED AREAS AND HOT SPOTS

This section describes approaches to evaluating elevated areas or hot spots in consideration of potential doses to receptors including the inadvertent intruder.

KEY POINTS

- The difference between a *hot spot* and an *elevated zone* is explained.
- EPA recommendations are given on traditional search techniques for hot spots.
- Remedial cost analysis can include ALARA cost calculations via SADA.
- A data gap exists for averaging hot spots away versus excavation.
- Hot spots can be identified through geostatistical interpolation (indicator kriging).

The HSA will probably indicate where an elevated soil sample is to be expected, perhaps simply through a record of a spill or leaking pipe (bias sampling). A spill might also be discovered accidentally through a random sampling campaign. However, identifying a potential elevated zone is not the same as determining its extent. One of the objectives of this white paper is to explore the effectiveness of projecting the vertical extent and shape of a subsurface elevated volume anomaly to the surface and then applying MARSSIM survey techniques. In other words, can sampling locations as a 2D search projected through the subsurface result in a quality evaluation of the subsurface? Also necessary is clarification of exactly what a hot spot or elevated area is. How is a hot spot found, and has the NRC already identified requirements for a hot spot in the subsurface? This white paper explores the thinking behind traditional and geostatistical approaches, while noting that all collected data are amenable to 3D representations with perhaps temporal adjustments.

NUREG/CR-7021 provides a geospatial modeling and decision framework for conducting a subsurface compliance survey and analysis for sites that have been remediated for radioactive contamination. The framework presented in Section 5 proposes a method to extend the MARSSIM guidance to the subsurface. It combines and organizes survey methods into a highly flexible sampling, modeling, and decision analysis approach that emphasizes the quality of decision-making throughout the investigation. In lieu of extraordinary costs associated with intense sampling and in lieu of complete subsurface removal, NUREG/CR-7021 acknowledges these prevailing circumstances and responds by focusing on the quality of the final compliance decision and the reasonable mitigation of uncertainty (Stewart 2012). This white paper explores combining the use of traditional searching for hot spots and the use of geospatial modeling.

The initial estimated $DCGL_V$ might be determined with initial subsurface soil results and various site-specific parameters including the "as is" width, depth, and thickness of the contaminated zone. Some sampling must be performed to estimate these parameters and the $DCGL_V$ via a RESRAD simulation. Comparison of mean results of contaminated samples to the DCGL provided by the simulation should establish whether an elevated zone exists.

The impact of any human disturbance from drilling, excavation for a basement, or a large-scale excavation of contaminated subsurface soils is also estimated and related as a $DCGL_W$.

Appendix J to NUREG-1757, Volume 2, Revision 2, provides guidance on how to develop exposure scenarios to an average member of the critical group for these and similar actions; intruder scenarios are considered (NRC 2020c). The mean contamination level and portion of the volume that is contaminated and brought to the surface directly impacts a surface $DCGL_W$. A $DCGL_V$ for the "as is" subsurface volume may be considerably different from the $DCGL_W$ developed for an intruder scenario depending on the exposure pathways involved. The revision to NUREG-1757, Volume 2, Appendix J, includes two examples using RESRAD simulations: modeling buried material and modeling backfilled basements. Appendix J also discusses basement excavation and well drilling. An SOF of the $DCGL_V$ and $DCGL_W$ may be required and applicable for most sites; cases are expected where the $DCGL_W$ developed for an intruder scenario could be dominant.

13.1 ELEVATED CONTAMINATED VOLUMES OR HOT SPOTS

The "User's Manual for RESRAD Version 6" defines a contaminated zone as a below ground volume within which the radionuclide concentrations in soil samples clearly exceed the background concentrations; however, the manual does not define "clearly" (Yu et al. 2001). Residual radioactivity for the purposes of the LTR criteria found in 10 CFR Part 20, Subpart E, means "radioactivity in structures, materials, soils, groundwater, and other media at a site resulting from activities under the licensee's control. This includes radioactivity from all licensed and unlicensed sources used by the licensee, but excludes background radiation" (from 10 CFR 20.1003.

So, if results of the scoping survey indicate an elevated zone within a contaminated zone beginning at some depth below the surface and continuing further down for some distance, what does that mean and what is the next step? RESRAD simulations with conservative values for cover, contamination zone areas, depths and thicknesses, and what might be the mean concentration could begin the estimation process. If the maximum concentration identified is used in the RESRAD simulation, the estimate will probably be too conservative.

An area of elevated activity might also be referred to as a *hot spot.* MARSSIM purposefully omitted this term because it often has different meanings based on operational or local program concerns (NRC 2000a). Because some of these meanings are inconsistent with MARSSIM concepts, the MARSSIM authors decided that there could be problems with defining the term and reeducating MARSSIM users in its proper use. Generally, an elevated area is an area that is above the DCGL; colloquially, it may be known as a *hot spot*. The size of an allowable subsurface hot spot is not known.

As a cumbersome example of the use of *hot spot* as an operational concern, the U.S. DOE in Order 5400.5 indicated the following:

> If the average concentration in any surface or below-surface area less than or equal to 25 m^2, exceeds the limit or guideline by a factor of $(100/A)^{1/2}$, [where A is the area (in square meters) of the region in which concentrations are elevated], limits for "hot-spots" shall also be developed and applied...In addition, reasonable efforts shall be made to remove any source of radionuclide that exceeds 30 times the appropriate limit for soil, irrespective of the average concentration in the soil.

Some facilities may use a multiplier of the background dose rate as an indicator of a hot spot and assign it according to their work procedures.

However, the ANSI/HPS Standard N13.59-2008, "Characterization in Support of Decommissioning Using the Data Quality Objectives Process" (ANS 2008), provides a generalized definition of a hot spot that might be applied to elevated areas or elevated volumes: “A general term that refers to an area of elevated contamination or radiation that 1) exceeds the average guideline level or 2) is markedly greater than the general contamination or radiation level” (ANS 2008).

Guidance on elevated areas in MARSSIM and NUREG-1757, Volume 2, was updated in Revision 2 of both documents. MARSSIM, draft Revision 2, notes conservatisms of application of the unity rule when multiple elevated areas are involved (NRC 2020b). NUREG-1757, Volume 2, Revision 2, in Sections I.2.3.1 and I.2.3.2, provides examples of different methods to address elevated areas and heterogeneity in radionuclide concentrations (NRC 2020c). Section I.3.3.3 also discusses the impact of area on dose for various radionuclides and pathways and provides guidance on consideration of area in developing alternative exposure areas. NRC guidance notes that site-specific modeling should be conducted to determine $DCGL_{EMC}$, but allows for consideration of area to make modifications to parameters, pathways, and exposure scenarios, with technical justification.

13.2 TRADITIONAL ELEVATED VOLUME SEARCHES

Additional sampling will be necessary in areas where the initial sample might qualify as an elevated volume. Nothing precludes random, bias, or grid sampling during a search survey but the EPA has suggested that additional sampling be conducted around the initial triggering location in a series of radial transects (see Figure 13-1). That way, the 3D extent of contamination can be more carefully defined. If the contaminated volume qualifies as elevated (i.e., the mean is greater than $DCGL_V$ or $DCGL_W$), its extent can be reasonably estimated. If the subsurface soil does not qualify as an elevated zone, that can also be established (EPA 1996). As a grid may or may not be established at this point, GPS measurements are a means for mapping or gridding locations later. Note that SADA will accept data from any sampling campaign.

A RESRAD simulation at this point can provide an initial $DCGL_V$ estimate[24] even with limited site-specific data. A decision is to be made as to performing a characterization survey and moving to the compliance phase or to refining the knowledge of the contaminated zone. Use of geophysical methods such as magnetometers, ground-penetrating radar, and electrical resistivity measurements may also guide investigation of elevated zones.

The star pattern search (see Figure 13-1) can be implemented to define the boundaries of the elevated zone boundary to concentrations less than the estimated $DCGL_V$. The search sampling is placed at a 10-m distance from the indicated elevated sampling point and then continued at 10-m intervals until the 3D boundary is identified; the initial direction may be intuitive such as selection of the next sampling location at a downgradient location. Both 2D and 3D graphs of the concentrations with distance or AOC maps will provide a visual tool in the assessment. The questions are how much of the volume with the higher concentrations needs to be removed to get the mean of the remaining (postexcavation) contaminated zone below the $DCGL_V$, where is the elevated zone actually located, and is it ALARA?

Current NRC guidance indicates the following:

> The core samples should be homogenized over a soil thickness that is consistent with assumptions made in the dose assessment, typically not exceeding 1 meter

[24] The estimated DCGL may change slightly as more data are collected on the contaminated zone dimensions and site-specific parameters are established. The NRC must approve the final DCGL.

> in depth. It is not acceptable to average radionuclide concentrations over an arbitrary soil thickness. Site-specific EMCs may also need to be developed to demonstrate regulatory compliance. Generic guidance has not yet been developed for performing an EMC for subsurface samples; therefore, licensees should discuss this matter with NRC staff on a case-by-case basis. (NRC 2006)

Each coring may contain several samples, but the first actually contaminated core segment begins at field measured levels of mean background plus two standard deviations of background.[25] Successive core segments can also be measured in the field. This sequence may have to be performed on several radial transects (three to eight of them, see Figure 13-1) from the hot spot to satisfy DQOs. Measurements in the field might be performed with ISOCS if gamma-emitters are involved. Some U.S. Army Corps of Engineers and DOE sites have also established field laboratories to expedite results for field decisions. Field measurement of samples ensures that use of resources is maximized, as field teams and equipment do not waste time and money mobilizing and demobilizing several times; the concept of do it once and done is encouraged. It may take time to set up the ISOCS device or a field laboratory, but the value of near real-time measurements for decision-making versus waiting for a laboratory result may justify the time spent. Adjustments to results may be required for a wet sample versus a laboratory dried sample, but a small percentage of the samples could be sent to an offsite laboratory for confirmation; field laboratories can also be set up to dry samples.

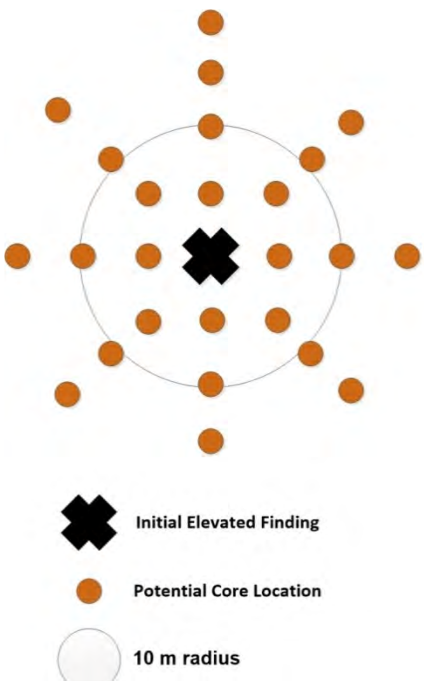

Figure 13-1 Search Pattern for Extent of Elevated Zone

Source: EPA 1996

[25] From Yu et al. 2001, page 3-6, and Yu et al. 2015, pages 233–234.

13.3 GEOSTATISTICAL SOFTWARE SEARCH APPROACHES FOR ELEVATED VOLUMES

Geostatistical interpolation (indicator kriging) may be used to identify potential hot spots. Any identified locations would then be further investigated as in MARSSIM when a scan flags an area for further information.

Although geostatistical software packages, such as VSP, that will search for an elevated area on 2D domains are available (see Section 6), this white paper examines the use of geostatistical approaches that exploit spatial relationships to develop a 3D contamination map based on measurement results from discrete points. The NRC has sponsored SADA,[26] which contains a 2D MARSSIM module as well as 3D capability. Both the EPA and the NRC have been principal sponsors of SADA. SADA may be downloaded after completion of a questionnaire from its Web site https://www.sadaproject.net/download.html. Other useful SADA documents, such as the user guide, may also be downloaded from the SADA Web site.

SADA provides methods for the exploration of environmental data that are categorized by depth during remedial investigations (generally soil and ground water). Data exploration tools include 2D and 3D data visualization options. 3D information is presented as multiple slices (layers) or by volume. The volume approach allows visualization of all depths at once (NRC 2003). The SADA user's manual (Stewart et al. 2009) is an excellent reference for exploring these methods.

SADA accepts map layers from GIS and allows the user to select a subregion of the site for geospatial and risk analyses. Geospatial analysis tools include methods for assessing spatial correlation among data, modeling spatial correlation, and producing concentration, risk, probability, variance, and cleanup maps. Spatial data can be interpolated via ordinary kriging, indicator kriging, inverse distance, or nearest neighbor methods. Although SADA has a MARSSIM module and performs elevated area searches with squares, rectangles, and triangles, it also extends the 2D search algorithm into a 3D probability search. SADA will determine the probability of discovery for a specified 3D grid and 3D object (see the SADA user's manual for details (Stewart et al. 2009)).

VSP contains a 2D version of an elevated area search. A projection of a 3D ellipsoid onto the surface would indicate coring locations. This may not be much of a limitation since all cores must be taken from the surface downward in any case. Not all such cores need be analyzed, but only the portion expected to contain residual radioactivity. In addition, ranked set sampling, already in VSP, might be used to reduce analytical costs. Indeed, much of a subsurface survey 3D design could proceed by using 2D layers. One would lose the capability of using 3D variograms to interpolate the subsurface; however, this may not result in a great loss of information, since the 3D variograms would be highly asymmetric in the vertical direction versus the horizontal and require a significant cost in samples for fitting a 3D variogram. Many such approximations may be needed to use 2D tools for a 3D problem.

One significant feature of SADA is the ability to construct a Bayesian Ellipgrid design based on a user-defined model that roughly estimates the probability that subsurface contamintion exists in different parts of the site. A 2D version of this could be just as useful. Once the hard data are collected at the 2D locations specified by the Baysian Ellipgrid, a secondary sampling plan could be designed using Markov-Bayes in 2D if such were developed in VSP. Markov-Bayes is

[26] SADA is a dedicated effort between the University of Tennessee, the U.S. Federal Government, and many other contributing institutions to provide a professional and free spatial modeling tool that promotes a consistent and thorough examination of spatially distributed environmental data.

a special application of the Markov model to a map of local prior probabilities (soft data). These concepts were developed for 3D in Section 7.3 of this white paper.

Since VSP already has 2D geostatistical tools, it may be possible to extend them to a 2D Markov-Bayes.

13.4 REMEDIAL EXCAVATION AND ALARA

13.4.1 SADA Tools for Remedial Analysis

SADA can produce site-specific cost-benefit curves that demonstrate the specific relationship between a given remedial cleanup goal and the corresponding cost. NRC cleanup goals are a concentration value of pCi/g. SADA also provides different strategies to determine future sample locations, depending on the choice of geospatial interpolator. The estimate rank approach identifies unsampled locations that are modeled to have high concentration levels relative to the existing data. SADA can be useful for verifying the extent of hot spot regions and is available for any of the interpolation schemes. It does not account, however, for data variability. Consequently, it may place sampling points at locations that are high in concentration values but are relatively well characterized. The variance rank approach fills new samples into unsampled locations that have high estimation variances. Since this approach gives no weight to the magnitude of concentrations, samples may appear where data are sparse but where corresponding concentrations are very low relative to the decision rule. This approach is available only with ordinary kriging. The percentile rank approach considers both the magnitude and variance so as to avoid sampling well-characterized hot spots or sparse areas with very low detected or nondetected values. The uncertainty rank approach places new samples in areas where there is the greatest uncertainty about exceeding a cleanup goal. It helps delineate the boundaries of an AOC. Finally, the secondary constraint approach allows the user to specify a minimum distance between any new sample locations and any previously sampled data (NRC 2003).

The cost/benefit analysis in SADA appears to be directly applicable to subsurface remedial activities without much change to SADA. SADA provides cost/benefit curves for a range of remedial action goals. These goals may range over the minimum and maximum sample values or may range over the corresponding human health risk values, ecological benchmark ratios, or custom analysis values.

13.4.2 As Low As Reasonably Achievable

Section 6 of NUREG-1757, Volume 2, Revision 1, provides details on the information needed to ensure that doses to the average member of the critical group are ALARA. Requested information includes (1) a cost-benefit analysis (or qualitative arguments) for the preferred option of removing residual radioactivity to a level that meets or exceeds the applicable limit and (2) a description of the licensee's preferred method for showing compliance with the ALARA requirement at the time of decommissioning. The NUREG suggests that the following information be included in the description of the development of the decommissioning goal (NRC 2006):

- a description of how the licensee will achieve a decommissioning goal below the dose limit
- a quantitative cost/benefit analysis
- a description of how costs were estimated

- a demonstration that the doses to the average member of the critical group are ALARA

Appendix N to NUREG-1757, Volume 2, Revision 2, continues with details of the benefits and costs for ALARA analyses. SADA can provide valuable input to the calculations described in that NUREG for subsurface remedial actions.

Table 13-1 Possible Benefits and Costs Related to Decommissioning

Possible Benefits	Possible Costs
Collective Dose Averted	Remediation Costs
Regulatory Costs Avoided	Additional Occupational/Public Dose
Changes in Land Values	Occupational Nonradiological Risk
Aesthetics	Transportation Direct Costs and Implied Risks
Reduction in Public Opposition	Environmental Impacts
	Loss of Economic Use of Site Facility

Source: NRC 2006, Table N.1

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APPENDIX A

GEOSPATIAL MODELING SOFTWARE TOOLS

Tables

Table A-1 Summary of Available Products for Performing Geostatistical Analysis

Source: Electric Power Research Institute, "Guidance for Using Geostatistics in Developing a Site Final Status Survey Program for Plant Decommissioning." Report No. 3002007554, issued May 2016 (EPRI 2016). https://www.epri.com/research/products/3002007554

Product	Cost	Dimensionality	Directed Workflow?	Exploratory Data Analysis	Sample Design / Optimization	Structural Analysis	Anisotropic Variograms	Point Kriging	Block Kriging	Universal Kriging	Co-Kriging	Indicator Kriging	Spatial-Temporal Kriging	Discontinuities / Complex Geometries	Conditional Simulation	Cross-Validation	Fate and Transport Modeling	Dose Assessment	Geographical Information System	Highlights
ASCEM (U.S. DOE)	Proprietary	3D														•	•			model assimilation with flow and transport predictions
Earth Volumetric Studio (C Tech)	High	3D		•	•	•	•	•				•							•	block diagram interface, treatment of geological lithification, borehole optimization
geoR and RGeostats (R Software) http://rgeostats.free.fr/	Free	3D		•		•	•	•	•	•	•	•		•	•	•				exemplar combination of breadth and width
Geostatistical Analyst (ESRI)	High	2D	•	•		•	•	•		•	•	•			•	•			•	high degree of user control, user-friendliness
GS+ (Gamma Design Software)	Low	2D		•		•	•	•	•	•	•	•		•	•	•				abundance of autocorrelation measures
GsTL (C++) http://gstl.sourceforge.net/	Free	3D						•		•	•	•			•					generic programming paradigm
HPGL (Python)	Free	3D				•	•	•		•	•	•			•					efficient and parallelized algorithms

Product	Cost	Dimensionality	Directed Workflow?	Exploratory Data Analysis	Sample Design / Optimization	Structural Analysis	Anisotropic Variograms	Point Kriging	Block Kriging	Universal Kriging	Co-Kriging	Indicator Kriging	Spatial-Temporal Kriging	Discontinuities / Complex Geometries	Conditional Simulation	Cross-Validation	Fate and Transport Modeling	Dose Assessment	Geographical Information System	Highlights
https://pypi.org/project/python-hpgl/#description																				
HydroGeoAnalyst (Schlumberger)	High	3D						●	●	●									●	integrated data management utilities
Isatis (Geovariances)	High	3D	●	●		●	●	●	●	●	●	●		●	●	●			●	journal file, principal component analysis, abundance of variogram model forms, block kriging in complex subregions, supported by active R&D
Kartotrak (Geovariances)	High	3D	●	●	●	●	●		●			●							●	real-time data streaming, highly structured workflow, MARSSIM and ISO 8550 sampling protocols
mGstat (MATLAB) http://mgstat.sourceforge.net/	Free	3D				●	●	●		●			●		●					interfaces for Gstat and SGeMS
Native command set (SAS)	Free	2D		●		●	●	●		●					●					automated exploration of many variograms
SADA (University of Tennessee) https://www.sadaproject.net/download.html	Free	3D	●	●	●	●	●	●			●	●			●	●		●	●	area of concern maps, math arithmetic, sampling optimization, remediation cost-benefit analysis

Product	Cost	Dimensionality	Directed Workflow?	Exploratory Data Analysis	Sample Design / Optimization	Structural Analysis	Anisotropic Variograms	Point Kriging	Block Kriging	Universal Kriging	Co-Kriging	Indicator Kriging	Spatial-Temporal Kriging	Discontinuities / Complex Geometries	Conditional Simulation	Cross-Validation	Fate and Transport Modeling	Dose Assessment	Geographical Information System	Highlights
SGeMS (Stanford) http://sgems.sourceforge.net/?q=node/77	Free	3D		●		●	●	●	●	●	●	●			●					optional command line interface, downscaling predictions, multipoint geostatistics
Surfer (Golden Software)	Low	2D		●		●	●	●	●	●				●		●			●	native scripting language
T-Progs (Lawrence Livermore) https://www.aquaveo.com/software/gms-pricing	Free	3D				●	●					●		●	●					transition probability/Markov chain geostatistics
VSP (Pacific Northwest National Laboratory)	Free	2D	●	●	●	●		●	●			●	●							Walsh's outlier test, data quality objective (DQO)-based sampling, economic analysis

Table A-2 Geospatial Analysis Software Tools

Source: Adapted from https://spatialanalysisonline.com/software.html

Product Name	Product Type	Free?	Web Site
ade4	Mathematical/statistical library	Y	http://cran.r-project.org/web/packages/ade4/index.html
Agent Analyst	Geosimulation	Y	http://resources.arcgis.com/en/help/agent-analyst/
AgentSheets	Geosimulation	N	http://www.agentsheets.com/
AltaMap suite (now Descartes)	Telecommunications/ visibility analysis	N	https://www.descartes.com/
ANN	Mathematical/statistical library	Y	http://www.cs.umd.edu/~mount/ANN/
ANUDEM	Terrain analysis	N	http://fennerschool.anu.edu.au/research/products/anudem-vrsn-53
AnyLogic	Geosimulation	N	http://www.anylogic.com/
ArcExplorer	Viewer	Y	https://www.esri.com/en-us/arcgis/products/explorer-for-arcgis
ArcGIS	GIS	N	http://www.esri.com/
ArcLogistics (ArcGIS Network Analyst)	Logistics	N	http://www.esri.com/software/arcgis/extensions/networkanalyst
AutoCAD Civil 3D	Visualization (2D and 3D)	N	https://www.autodesk.com/products/autocad-civil-3d/overview
Bentley MicroStation Geographics	GIS	N	https://www.bentley.com/en/products/product-line/modeling-and-visualization-software/microstation
BoundarySeer	Specialized data analysis	N	https://www.biomedware.com/software/boundaryseer/
Cadcorp SIS	GIS	N	http://www.cadcorp.com/products/
CadnaA	Noise mapping	N	http://www.datakustik.com/en/products/cadnaa/
Calpuff View	Emergency and hazard assessment	N	http://www.weblakes.com/calpuff/calpuff_overview.html
CARIS	GIS	N	http://www.teledynecaris.com/en/home/
Cartomap	Viewer	Y	http://cartoworld.com/free-cartomap-software/
Cellular Expert	Telecommunications/ visibility analysis	N	http://www.cellular-expert.com/
ClusterSeer	Cluster analysis	N	https://www.biomedware.com/software/clusterseer/
CommunityViz	Visualization (2D and 3D)	N	http://communityviz.city-explained.com/
Coordinate Calculator	Specialized mapping	Y	http://www.tatukgis.com/Products/CoordinateCalculator/Description.aspx

Product Name	Product Type	Free?	Web Site
CrimeStat IV	Crime analysis	Y	https://nij.ojp.gov/topics/articles/crimestat-spatial-statistics-program-analysis-crime-incident-locations
Cube	Traffic simulation and forecasting	N	http://www.citilabs.com/software/cube/
DEPTHMAP	Telecommunications/ visibility analysis	Y	http://www.spacesyntax.net/software/
Didger	Specialized mapping	N	http://www.goldensoftware.com/products/didger/
DYNAMEQ	Traffic simulation and forecasting	N	https://www.inrosoftware.com/en/products/dynameq/
Emme	Traffic simulation and forecasting	N	http://www.inro.ca/en/products/emme/
ENVI	Remote-sensing analysis	N	https://www.harrisgeospatial.com/Software-Technology/Software
EOS Land Viewer	Web-based interactive map viewer	Y/N	https://eos.com/landviewer
ER Mapper	Specialized mapping	N	https://www.hexagongeospatial.com/products/power-portfolio/other-producer-products/
ERDAS Imagine (now Hexagon Geospatial)	GIS	N	https://www.hexagongeospatial.com/products/power-portfolio/erdas-imagine
eRouteLogistics	Logistics	N	http://www.e-iit.com/RoutePlanning.html
Farsite	Emergency and hazard assessment	Y	https://www.firelab.org/project/farsite
FDO	GIS tools	Y	http://fdo.osgeo.org/
Feature Analyst	Terrain analysis	N	https://www.textronsystems.com/products/feature-analyst
FloodWorks	Hydrological analysis	N	https://www.innovyze.com/en-us/products/icmlive
FME	Specialized mapping	N	http://www.safe.com/solutions/for-applications/esri-arcgis/
Fractal Terrains	Specialized mapping	N	http://www.profantasy.com/products/ft.asp
Fragstats	Landscape analysis	Y	http://www.umass.edu/landeco/research/fragstats/fragstats.html
Global Optimization Toolbox (MATLab)	Optimization algorithms	N	https://www.mathworks.com/products/global-optimization.html?ref=pfo
GALib	Genetic algorithms	Y	http://lancet.mit.edu/ga/
GAM/K	Cluster analysis	Y	http://www.ccg.leeds.ac.uk/software/gam/
GDAL	GIS tools	Y	http://www.gdal.org/
GenaMap	GIS	N	https://genasys.com/products/ccaas-solutions/

Product Name	Product Type	Free?	Web Site
GeoDa	Exploratory data analysis (EDA/ESDA)	Y	https://spatial.uchicago.edu/software
GeoExpress	Image handling	N	https://www.extensis.com/geoexpress
Geographic Calculator	GIS tools	N	http://www.bluemarblegeo.com
Geographically Weighted Regression (GWR)	Statistical analysis	N	http://gwr.maynoothuniversity.ie/gwr4-software/
Geomatica	GIS	N	http://www.pcigeomatics.com//
Geomedia (now Hexagon)	GIS	N	https://www.hexagonsafetyinfrastructure.com/products/utilities-and-communications-products/advanced-utility-gis
Geoplot	Specialized mapping	N	http://www.geoscan-research.co.uk/page9.html
Geostat	Geostatistical analysis	N	http://www.geostat.com/
GeoVista Software	Exploratory data analysis (EDA/ESDA)	Y	https://www.geovista.psu.edu/outreach/software/
GMT	GIS tools	Y	https://www.generic-mapping-tools.org/
Grapher	Graphing	N	http://www.goldensoftware.com/products/grapher/grapher.shtml
GRASP	Specialized data analysis	Y	http://www.ticra.com/products/software/grasp
GRASS	GIS	Y	http://grass.osgeo.org/
Groundwater Modeling System (GMS)	Hydrological analysis	N	http://www.aquaveo.com/software/gms-groundwater-modeling-system-introduction
GS+	Geostatistical analysis	N	https://geostatistics.com/
Hawth's Tools	GIS tools	Y	http://www.spatialecology.com/
ICS Telecom	Telecommunications/ visibility analysis	N	https://atdi.com/
Idrisi	GIS	N	http://www.clarklabs.org/
ILOG CPLEX	Optimization	(Y)	https://www.ibm.com/products/ilog-cplex-optimization-studio
ILWIS	GIS	Y	https://www.itc.nl/ilwis/
IMMI	Noise and air pollution	N	https://www.woelfel.de/produkte/immissionsprognose-immi.html
InfoWorks	Hydrological analysis	N	https://www.innovyze.com/en-us/products/infoworks-icm
InstantAtlas	Specialized mapping	N	http://www.instantatlas.com
ISATIS	Geostatistical analysis	N	http://www.geovariances.com/
Landscape Fragmentation Tool	Landscape analysis	Y	http://clear.uconn.edu/%5C/tools/lft/lft2/index.htm

Product Name	Product Type	Free?	Web Site
LandSerf	Terrain analysis	Y	http://www.landserf.org
LEDA	Optimization	N	http://www.algorithmic-solutions.com/
LIDAR Analyst	Terrain analysis	N	https://www.textronsystems.com/products/lidar-analyst
LINDO	Optimization	N	http://www.lindo.com/
LOLA	Location and layout analysis	Y	http://www.mathematik.uni-kl.de/opt/forschung/forschung-und-industrieprojekte/stanlay/lolola/
LP-Solve	Optimization	Y	http://lpsolve.sourceforge.net/5.5/
Manifold/Radian	GIS	N	http://www.manifold.net/
Map Comparison Kit	Spatio-temporal analysis	Y	http://www.riks.nl/products/Map-Comparison-Kit
MapGuide	GIS	Y	https://www.osgeo.org/projects/mapguide-open-source/
MapInfo	GIS	N	https://www.pitneybowes.com/us/location-intelligence/geographic-information-systems/mapinfo-pro.html
MapMerger	Specialized mapping	N	https://www.harris.com/solution/mapmerger-geospatial-vector-conflation
MAPresso	Specialized mapping	Y	http://www.mapresso.com/
MapServer	Specialized mapping	Y	http://mapserver.org/
MapText/Label EZ	Specialized mapping	N	http://www.maptext.com/
Maptitude (Caliper)	GIS	N	http://www.caliper.com/
MapTools	GIS tools		www.maptools.org
MAPublisher	Specialized mapping	(Y)	https://www.avenza.com/mapublisher/
MapViewer	GIS	N	https://www.goldensoftware.com/products/mapviewer
MASON	Geosimulation	Y	http://cs.gmu.edu/~eclab/projects/mason/
MATLab plus toolboxes	Mathematical/statistical library	N	http://www.mathworks.com/
MATSim	Geosimulation	Y	http://matsim.org/
Mondrian	Visualization (2D and 3D)	Y	http://www.theusrus.de/Mondrian/
NatureServe Vista	Emergency and hazard assessment	N	https://www.natureserve.org/conservation-tools/natureserve-vista
NetLab	Neural networks	Y	https://www2.aston.ac.uk/eas/research/groups/ncrg/resources
NetLogo	Geosimulation	Y	http://ccl.northwestern.edu/netlogo/
NOISEMAP	Noise mapping		http://www.noisemap.ltd.uk/wpress/
NuMAP	Neural networks	(Y)	http://www.uta.edu/faculty/manry/new_software.html
OpenLayers	Specialized mapping	Y	http://openlayers.org/
OpenMap	GIS tools	Y	https://github.com/openmap-java/openmap

Product Name	Product Type	Free?	Web Site
Oriana	Directional analysis	N	http://www.kovcomp.com
OSSIM	Image handling	Y	http://trac.osgeo.org/ossim/
PASSaGE	Specialized data analysis	Y	http://www.passagesoftware.net/
PCRaster	GIS	Y	http://pcraster.geo.uu.nl/
PostGIS	GIS	Y	http://postgis.refractions.net/
PySal	Mathematical/statistical library	Y	https://spatial.uchicago.edu/software
QGIS	GIS	Y	https://www.qgis.org/en/site/
R Spatial	Mathematical/statistical library	Y	http://cran.r-project.org/web/views/Spatial.html
R2V	GIS tools	N	http://www.ablesw.com/r2v/index.html
REACT	Logistics	N	http://www.mjc2.com/
Repast Simphony	Geosimulation	Y	https://repast.github.io/index.html
RiverTools	Hydrological analysis	N	http://www.rivix.com/
RoadEng	Specialized mapping	N	http://www.softree.com
Rookcase	Statistical analysis	Y	http://www.lpc.uottawa.ca/data/scripts/
RouteSmart	Logistics	N	http://www.routesmart.com/
SAGA	GIS	Y	http://www.saga-gis.org/
SAGE2001 (SAGE2005)	Geostatistical analysis	N	http://www.isaaks.com/
SAM	Statistical analysis	Y	http://www.ecoevol.ufg.br/sam/
SANET	Network analysis	Y	http://sanet.csis.u-tokyo.ac.jp/
SaTScan	Cluster analysis	Y	http://www.satscan.org/
Smallworld	GIS	N	https://www.ge.com/digital/applications/geospatial-network-modeling-solutions-utilities
Software listing	GIS tools	N	http://ecat.giscafe.com/index.php
SOM Toolbox	Neural networks	Y	http://www.cis.hut.fi/projects/somtoolbox/
SpaceStat	Statistical analysis	N	https://www.biomedware.com/software/spacestat/
Spatial Manager	GIS/mapping package	N	http://www.spatialmanager.com
Spdep	Mathematical/statistical library	Y	http://cran.r-project.org/web/packages/spdep/index.html
SPLANCS	Statistical analysis	Y	http://cran.r-project.org/web/packages/splancs/index.html
SPSS (IBM)	Statistical analysis	N	https://www.ibm.com/analytics/us/en/technology/spss/
StarLogo	Geosimulation	Y	https://education.mit.edu/project/starlogo-nova/

Product Name	Product Type	Free?	Web Site
STARS	Spatio-temporal analysis	Y	http://regionalanalysislab.org/index.php/Main/STARS
STATA/IC	Statistical analysis	N	http://www.stata.com/
Surfacewater Modeling System (SMS)	Hydrological analysis	N	https://www.aquaveo.com/software/sms-surface-water-modeling-system-introduction
Surfer	Graphing	N	https://www.goldensoftware.com/products/surfer
Surfit	Specialized mapping	Y	http://surfit.sourceforge.net/surfit/index.html
SurGe	Specialized mapping	Y	http://surgeweb.sweb.cz/
SWARM	Geosimulation	Y	http://www.swarm.org
Synchro and SIMTraffic	Traffic simulation and forecasting	N	http://www.trafficware.com/
TAP	Telecommunications/ visibility analysis	N	http://www.softwright.com/products/tap-software/
TAS (Whitebox)	Terrain analysis	Y	https://jblindsay.github.io/ghrg/Whitebox/index.html
TatukGIS	GIS tools	N	http://www.tatukgis.com/
TatukGIS Viewer	Viewer	Y	http://www.tatukgis.com/Products/EditorViewer/Description.aspx
TAUDEM	Terrain analysis	Y	http://hydrology.usu.edu/taudem/taudem5/index.html
TdhGIS	Vector-based spatial analysis	Y	https://www.tdhgis.com/
TNTmips	GIS	(Y)	https://www.microimages.com/
TransCAD	Network analysis	N	http://www.caliper.com/tcovu.htm
TransModeler	Traffic simulation and forecasting	N	http://www.caliper.com/transmodeler/
Truckstops	Logistics	N	https://www.truckstopsrouting.com/us/
TSIS-CORSIM	Traffic simulation and forecasting	N	http://mctrans.ce.ufl.edu/featured/TSIS/
uDig	GIS	Y	http://udig.refractions.net/
UrbanSim	Geosimulation	Y	http://www.urbansim.org/
Vincenty	GIS tools	Y	http://www.ga.gov.au/earth-monitoring/geodesy/geodetic-techniques/calculation-methods.html
Virtual Terrain Project	Visualization (2D and 3D)	Y	http://vterrain.org
VISUM	Traffic simulation and forecasting	N	http://vision-traffic.ptvgroup.com/en-us/products/ptv-visum/

Product Name	Product Type	Free?	Web Site
Watershed Modeling System (WMS)	Hydrological analysis	N	http://www.aquaveo.com/software/wms-watershed-modeling-system-introduction
What's Best	Optimization	N	http://www.lindo.com/
WinBUGS/GeoBUGS	Statistical analysis	Y	http://www.mrc-bsu.cam.ac.uk/software/bugs/thebugs-project-geobugs/
WindNinja	Specialized mapping	Y	http://www.firelab.org/project/windninja
WindWizard	Specialized mapping	(Y)	http://www.firelab.org/project/windwizard
Xpress-MP	Optimization	(Y)	http://www.fico.com/en/products/fico-xpress-optimization

Table A-3 Free Geostatistical Software Available

Name	Languages/OS	Capabilities
Agromet	Unix/Windows/C++	V-K-C-2D
Cosim	Windows/Fortran	S-2D
ExploStat	Windows	V-K-O-C-2D-G
E{Z}-Kriging	Windows	V-K-2D
Geo-EAS	Windows	V-K-2D
GeoPack	Windows	V-K-C-2D
GeoDa	Windows	O-2D
Geostatistical Toolbox	DOS	V-K-C-3D
GMT	Unix/C	O-2D
GRNN	Windows	O-2D
GSLIB	Fortran 77	V-K-C-3D-S
Gstat	Linux, Windows/C/R	V-K-C-3D-S
ISIM3D	Windows/C	S-3D
Kriging	Unix/C	K-2D
SADA	Windows	V-K-O-3D-G
SAGA GIS	Windows	V-K-O-2D-G
SGS	Linux, C	K-S-2D
S-GeMS	Windows, Linux, C++	V-K-C-3D-S
Spherekit	Unix, C	K-O-2D
Surface III	Mac	K-O-2D
Surfit	Windows, C++	O
UNCERT	Unix/Cs	V-K-O-C-2D-G
Variowin	Windows	V-2D
Vesper	Windows	V-K-2D

Source: https://wiki.52north.org/AI_GEOSTATS/WebHome

Key: V = Variography K = Kriging C = Co-Kriging S = Simulations G = GIS functions
O = Other Estimators (NN, IDW, splines) 2D/3D = maximum dimensions

Table A-4 Software Considered by Goovaerts (2010)

Name	Cost	Reference/Note[a]
Agromet	Free	Bogaert et al. (1995)
AUTO-IK	Free	Goovaerts (2009)
BMELib	Free	Christakos et al. (2002)
COSIM	Free	ai-geostats Web site[b]
EVS (C-Tech)	High	C Tech Development Corporation
GCOSIM3D/ISIM3D	Free	Gomez-Hernandez and Srivastava (1990)
Gen Stat	Free, Low	Payne et al. (2008)
GEO-EAS	Free	Englund and Sparks (1988)
GeoR	Free	Ribeiro and Diggle (2001)
Geostat Analyst	High	Extension for ArcGIS
Geostatistical Toolbox	Free	Froidevaux (1990)
Geostokos Toolkit	High	ai-geostats Web site[a]
GS+	Moderate	Robertson (2008)
GSLIB	Free	Deutsch and Journel (1998)
Gstat C,R	Free	Pebesma and Wesseling (1998)
ISATIS (Geovariances)	High	www.geovariances.com
MGstat	Free	ai-geostats website[a]
SADA (UT Knoxville)	Free	Spatial analysis and decision assistance
SAGE 2001	Moderate	Isaaks (1999)
SAS/STAT	High	SAS Institute Inc. (1989)
S-GeMS	Free	Remy et al. (2008)
SPRING	Free	Camara et al. (1996)
Space-time routines	Free	De Cesare et al. (2002)
STIS (TerraSeer)	Moderate	AvRuskin et al. (2004)
Surfer	Moderate	Golden Software, Inc.
Uncert	Free	Wingle et al. (1999)
Variowin	Free	Pannatier (1996)
VESPER	Free	Minasny et al. (2005)
WinGslib	Low	www.statios.com

a. References are found in the list in the main report.

b. The content of Web site from www.ai.geostats.org is now located at https://wiki.52north.org/AI_GEOSTATS/WebHome.

Table A-5 Decision Support Tools Reviewed by Sullivan (2002)

Software Decision Support Tool	Developer	Description/Comment
ArcView	Environmental Systems Research Institute (ESRI)	Most widely used GIS. Visualization and data interpretation. Data management.
API-DSS	American Petroleum Institute	Fate and transport and risk assessment.
BIOPLUME III	Rice University	Decision support for MNA[a]
BIOSCREEN	Air Force	Screening tool for decision support on MNA.
DQO-PRO	Pacific Northwest Laboratory	Site characterization and data collection.
ELIPGRID-PC	Pacific Northwest Laboratory	Site characterization, hot spot determination.
EVS (Environmental Visualization System)	CTECH	Site characterization, contaminant characterization, visualization.
FIELDS (**Fi**eld **E**nvironmenta**L** **D**ecision **S**upport)	U.S. Environmental Protection Agency	Extensions to ArcView for improved decision support on characterization and contaminant definition.
GMS (Groundwater Modeling System)	University of Utah	Visualization and geostatistical analysis of contaminant data.
MNAtoolbox	Sandia National Laboratory	Screening tool for decisions on the applicability of monitored natural attenuation at a site.
RAAS (Remedial Action Assessment System)	Pacific Northwest Laboratory	Compares remedial alternatives based on costs.
RIP	Golder and Associates	Definition of contaminated zones and risk assessment.
ROAM (Remedial Options Assessment Model)	Electric Power Research Institute	Comparison of effectiveness of remedial alternatives in reducing contaminant concentrations.
SADA (Spatial Analysis and Decision Assistance)	University of Tennessee	Site characterization, contaminant characterization, cost/benefit, and human and ecological risk assessment.
VSP (Visual Sample Plan)	Pacific Northwest Laboratory	Helps develop a sampling plan to meet DQO objectives.

[a] MNA = Monitored Natural Attenuation

APPENDIX B

ELECTRIC POWER RESEARCH INSTITUTE REVIEW OF SADA (EPRI 2016, SECTION 5.1.6)

Figures

The University of Tennessee and Oak Ridge National Laboratory collaborated on the development of Spatial Analysis and Decision Assistance (SADA). The main purpose of the software is to integrate human health and ecological risk assessment with geospatial analysis to support environmental restoration projects. The U.S. Nuclear Regulatory Commission (NRC) funded the SADA project.

The software includes features that make it a good candidate for use in nuclear decommissioning applications, including modules for “Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)” (NRC 2000) analysis, secondary sampling design, and cost-benefit analysis for remediation. Stewart and Purucker (2011) provide more information.

User Interface: The SADA graphics user interface (GUI) is composed of a traditional dropdown menu, a task bar where data structures and objectives are specified, and three subwindows. The first subwindow is a list of required steps based on the current objective. The second subwindow contains a menu where the user specifies parameters and settings for the current analysis step.

The third subwindow is a viewer with two-dimensional (2D) and three-dimensional (3D) capabilities.

Each analysis progresses as an interview, in which the software guides the users through a series of logical steps to accomplish their objective. Possible objectives include plot data, model spatial correlation, interpolate, identify area of concern, calculate cost of cleanup, and develop sample design. Each step in the process presents the user with questions or options specific to the task at hand. Some steps run small interim models that are needed before reaching the final result.

Data may be imported through several different file formats, but the most common is a CSV file format specifying for each data point spatial coordinates and the contamination value, and optionally the analyte or radionuclide name, whether detection occurred, the media, the sample ID, and the region name. Layers from other geographic information system (GIS) software products can be imported from .shp or .dxf files, or from graphics files. SADA also has its own binary file so entire projects can be saved and retrieved.

SADA includes basic GIS capabilities to manage different layers or to identify user-defined areas or polygons that may be used in downstream analysis.

Data Analysis and Manipulation: SADA includes a broad set of exploratory data analysis options including univariate and bivariate statistical metrics, histograms, cumulative distribution functions, statistical tests (i.e., Sign test, Wilcoxon Rank Sum test), and scatterplots. Among the unique statistical metrics are a 95th-percentile mean prediction and statistics for the subset of data points below or above the detection limit.

SADA includes other tools for data analysis and manipulation:

- Sample locations can be plotted in 2D and 3D space with color to delineate contamination levels. Values exceeding thresholds can be highlighted to draw the user’s attention to areas of concern.

- SADA includes two transformation methods: normal-score transformation and unit transformation.

- For structural analysis, SADA generates sample variograms and automatically fits analytical variograms. The user can manually override variogram parameters as needed.
- SADA includes helpful ways to investigate anisotropy in 3D space. For one, the user can generate variograms along any direction. Also, the user can view variogram surfaces (as in Figure B-1) along any plane.
- SADA includes co-regionalization modeling options to facilitate the development of co-kriging variograms.

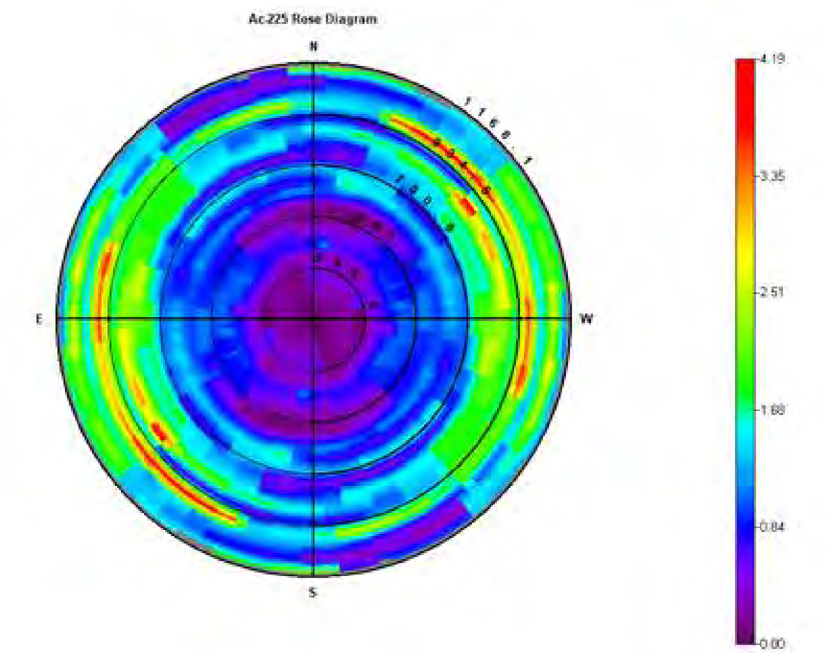

Figure B-1 Variogram Surface in SADA

Source: Stewart et al. 2009, p. 312

Interpolation: Geostatistical interpolation supports a number of the different possible analysis objectives within SADA. SADA includes ordinary kriging, indicator kriging, and co-kriging. The user can specify the rectilinear grid on which predictions are made and an ellipsoidal search neighborhood. The software also includes sequential Gaussian simulation and sequential indicator simulation.

SADA includes different postprocessing and visualization capabilities to draw insight from geostatistical interpolations:

- Like other software products, SADA can generate maps for the kriging mean, kriging variance, or probability of exceeding a threshold.
- SADA can generate area of concern maps indicating contiguous areas or volumes where thresholds of interest are exceeded. Using different kriging percentiles, confidence intervals around an area of concern can be generated. For instance, Figure B-2 illustrates the insight gained by superimposing the area of concern maps

based on the 25th, 50th, and 75th kriging percentiles. (While not shown here, SADA can also generate spatial maps illustrating the risk of declaring radiological activity acceptable when it is actually above the site release criteria, or vice versa.)

- For viewing contamination in 3D, SADA includes color maps of the domain, cutaways of the domain, semitransparent color maps, isosurfaces, and sample location rendering.

- Surface elevation data can be imported, allowing surface maps corresponding to elevation. Then, contamination color maps can be overlaid on the surface maps to allow visual investigation of correlation between elevation and contamination.

- SADA includes *map arithmetic*, whereby interpolation maps can be transformed in accordance with user-defined functions. Multiple maps can be involved in arithmetic; for example, contamination maps can be added or subtracted. This capability could be used, for instance, to generate geostatistical predictions for the sum of risk ratios. In accordance with MARSSIM, the sum of risk ratios should be less than unity throughout the domain.

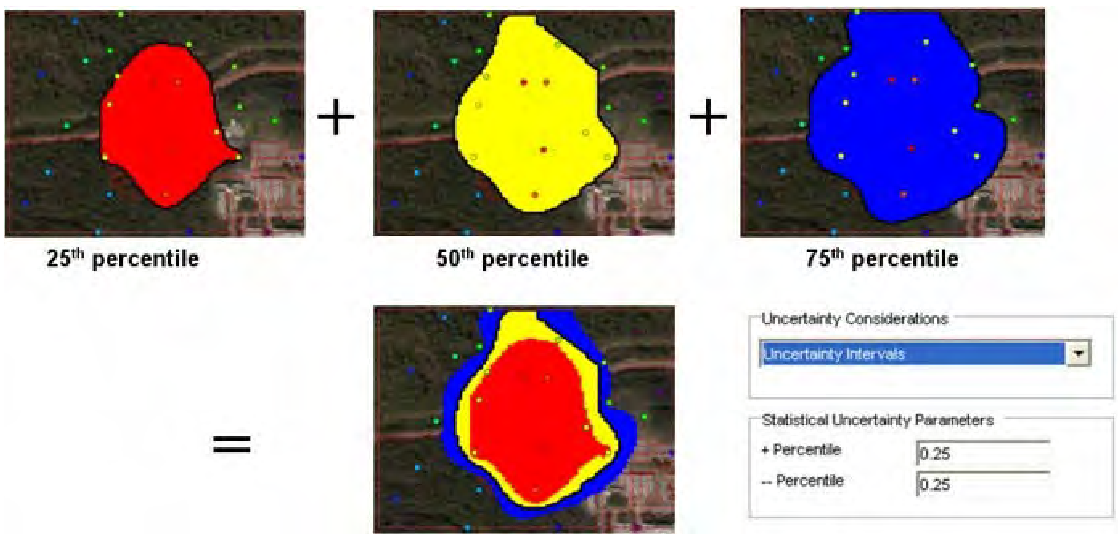

Figure B-2 Area of Concern Mapping in SADA

Source: Stewart et al. 2009, p. 439

Other Features: One distinguishing feature of SADA is its inclusion of human health and ecological risk modules based on the U.S. Environmental Protection Agency's (EPA's) risk assessment guidance for superfund (EPA 1989). While most other software products expect the user to input thresholds, SADA has embedded modules to calculate the risk of adverse consequences as a function of analyte, media, exposure pathways, and the future use scenarios for the site. For this analysis, SADA relies on a toxicity profile database and an ecological benchmark database, both of which are maintained regularly and downloadable for free at https://www.sadaproject.net/download.html. Currently, SADA is designed to address only hazardous waste assessments at environmental sites. It does not include a derived concentration guideline database for radionuclides.

With respect to remediation planning, SADA has the capability to develop cost versus decision threshold plots based on geostatistical interpolations. The cost calculation includes both contaminated material and overburden (i.e., uncontaminated material removed to access contaminated materials). The overburden calculation can include material excavated to create a benching angle required for safety concerns.

SADA also includes an extensive set of primary and secondary sampling design options. Among the secondary sampling design options are the following:

- Adaptive fill and local index of spatial association designs—Sample locations are determined to fill gaps, prevent clustering, and improve uniformity.
- Threshold radial—Sample locations are added in a pattern around samples with particularly high contamination.
- Area of concern boundary—Sample locations are added around the boundary of areas of concern identified via geostatistical interpolation (see Figure B-3).
- Check and cover—Sample locations are added to achieve a balance between areas of greatest concern while providing some coverage in those areas thought to be unaffected.
- Restricted areas—Samples are prevented in certain user-defined geological layers.

While not related to geostatistics, the latest version of SADA includes a MARSSIM objective, in which the user is guided through the various steps involved in a MARSSIM assessment. For instance, Figure B-4 shows a Wilcoxon Rank Sum test to determine whether there is statistical evidence that the residual contamination in the survey unit is different from the residual contamination in the background unit.

Accessibility: The latest version of SADA (5.0) for Windows is available at for free at https://www.sadaproject.net/download.html. SADA is regularly updated and is supported by national conferences, training, and a continually growing body of documents and applications.[1]

[1] As of this writing SADA no longer has support for maintenance or updates

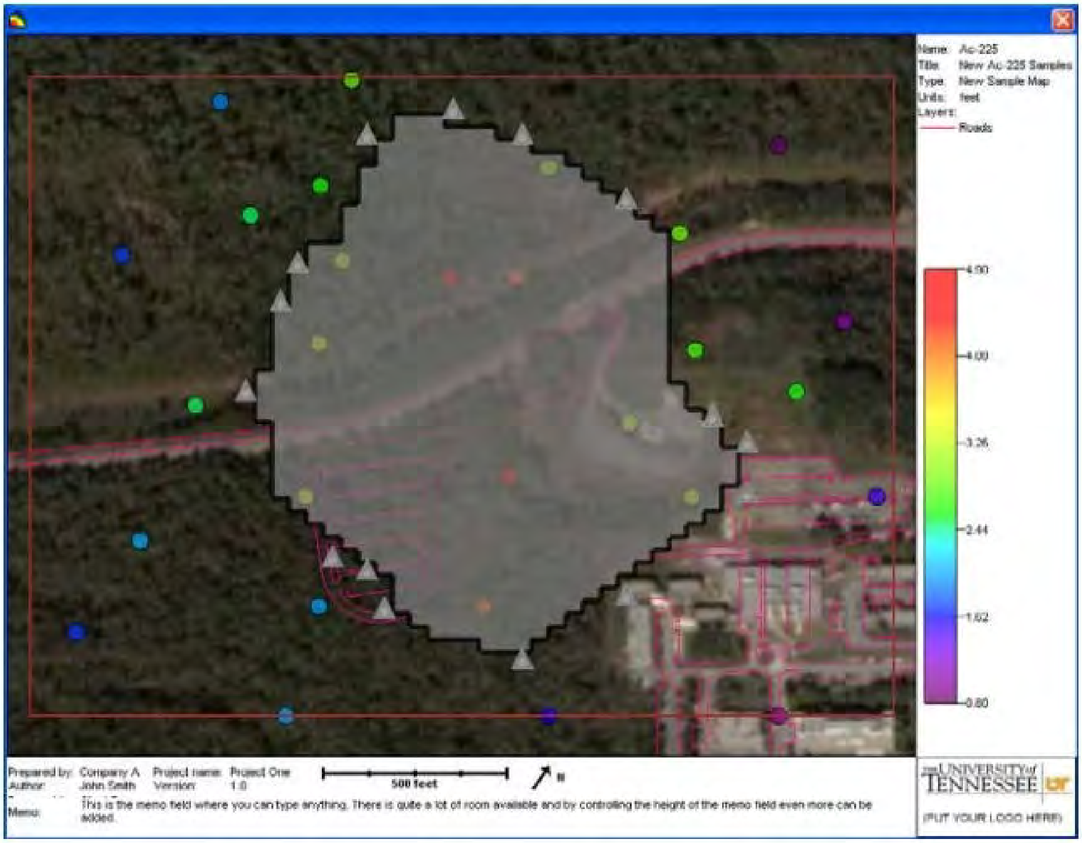

Figure B-3 Area of Concern Boundary Sampling Design in SADA (triangles indicate recommended samples)

Source: Stewart et al. 2009, p. 24

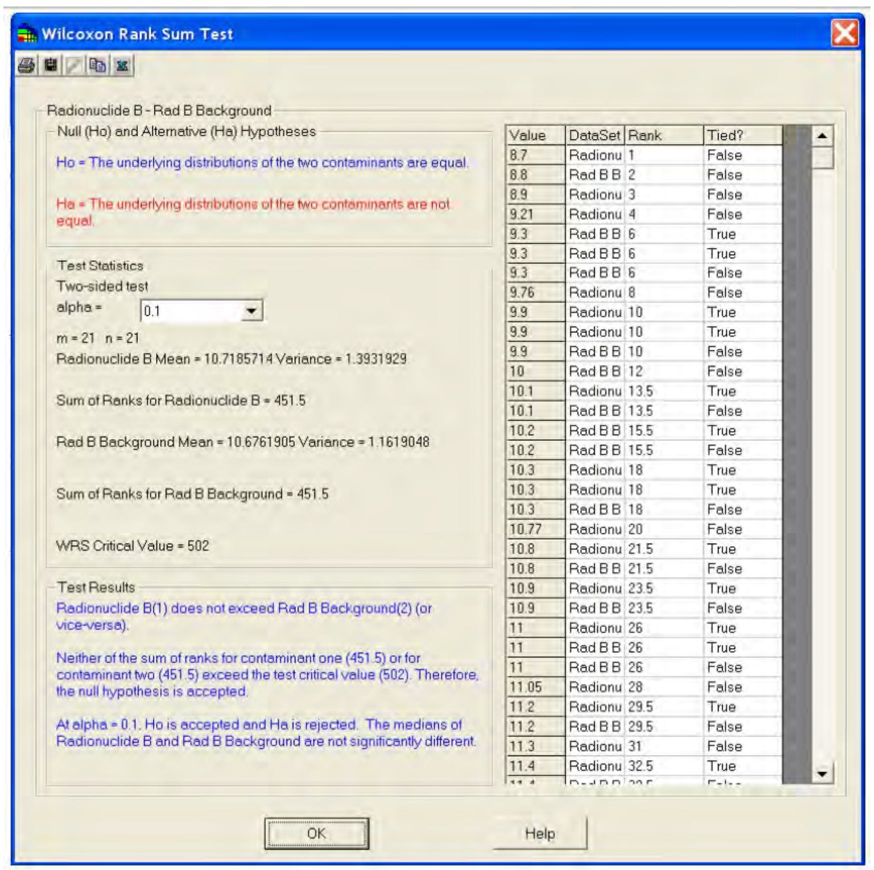

Figure B-4 Wilcoxon Rank Sum Test in SADA: Definition (top) and Results (bottom)

Source: Stewart et al. 2009, pp. 131–132

References:

Electric Power Research Institute (2016). "Guidance for Using Geostatistics in Developing a Site Final Status Survey Program for Plant Decommissioning," M.J. de Smith, M.F. Goodchild, and P.A. Longley, EPRI 3002007554, Palo Alto, CA, May 27, 2016. https://www.epri.com/research/products/3002007554

Stewart, R.N., and S.T. Purucker (2011). "An Environmental Decision Support System for Spatial Assessment and Selective Remediation," Environmental Modeling & Software, 27(6):751–760, June 1, 2011.

Stewart, R., Welsh, C., Purucker, T., and Stewart, D. (2009). "An Introduction to Spatial Analysis and Decision Assistance (SADA), Environmental Applications for Version 5, User Guide," University of Tennessee, Knoxville, TN, December 19, 2009. https://www.sadaproject.net/documentation.html

U.S. Environmental Protection Agency (1989). "Risk Assessment Guidance for Superfund Volume II, Environmental Evaluation Manual," EPA/540/1-89/001, Washington, DC, March 1989.

U.S. Nuclear Regulatory Commission (2000). "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)," NUREG 1575, Revision 1; EPA 402-R-97-016, Revision 1; DOE/EH 0624, Revision 1; U.S. Department of Defense; U.S. Department of Energy; U.S. Environmental Protection Agency; and U.S. NRC; Washington, DC, August 2000, ADAMS Accession No. ML003761445.

APPENDIX C

ELECTRIC POWER RESEARCH INSTITUTE REVIEW OF VSP (EPRI 2016, SECTION 5.1.8)

Figures

Visual Sample Plan (Pacific Northwest National Laboratory)

Pacific Northwest National Laboratory developed Visual Sample Plan (VSP) for environmental management applications, with specific focus on sample design. VSP has been used in the context of radiological site characterization at various U.S. Department of Energy (DOE) sites, including at a former beryllium machine shop at Los Alamos National Laboratory, at the Portsmouth and Paducah gaseous diffusion plants, and at the Nevada Test Site. VSP has also been used at nuclear power plants in the design of decommissioning final status surveys (FSSs).

The geostatistical capabilities of VSP can be accessed directly to develop kriging maps; however, their main purpose is to enable the sample design methods described in the “Other Features” section below. The geostatistical analysis available in VSP is for two-dimensional domains only.

User Interface: VSP is designed for project managers and users who are not statistical experts. There is an extensive user manual, a help manual, and workflow guides to assist the user throughout analysis. A traditional Windows graphics user interface (GUI) is available with a dropdown menu and toolbars for specification of sampling goals, analysis tools, visualization, and other factors.

Sample data are imported through a tab-delimited text file with a simple organizational structure. The software also accepts .dxf or .shp files to depict other spatial features (e.g., site maps and aerial pictures). Users can also draw their own spatial features and define their domain of interest using tools provided within VSP. For instance, VSP includes a number of computer-aided design (CAD) features to enable the user to define interior layouts.

The software includes various interfaces, including a map view, a graphical view for conveying certain results such as statistical plots, a report view that compiles the analysis into an organized report, and an interactive three-dimensional view.

Data Analysis and Manipulation: The Data Analysis menu of VSP includes standard features such as the compilation of statistical metrics and the generation of histogram and Q-Q plots. Some less common features include the implementation of Walsh’s outlier test and the Shapiro-Wilk test of normality.

Useful data manipulation features include the ability to filter, manually exclude, and transform data. Normal-score or logarithmic transformations are available.

Figure C-1 depicts the Variogram Model menu of VSP. Users have the option to specify their own variogram, including the model form and model parameters for up to three nested structures. Anisotropic variograms cannot be specified in VSP.

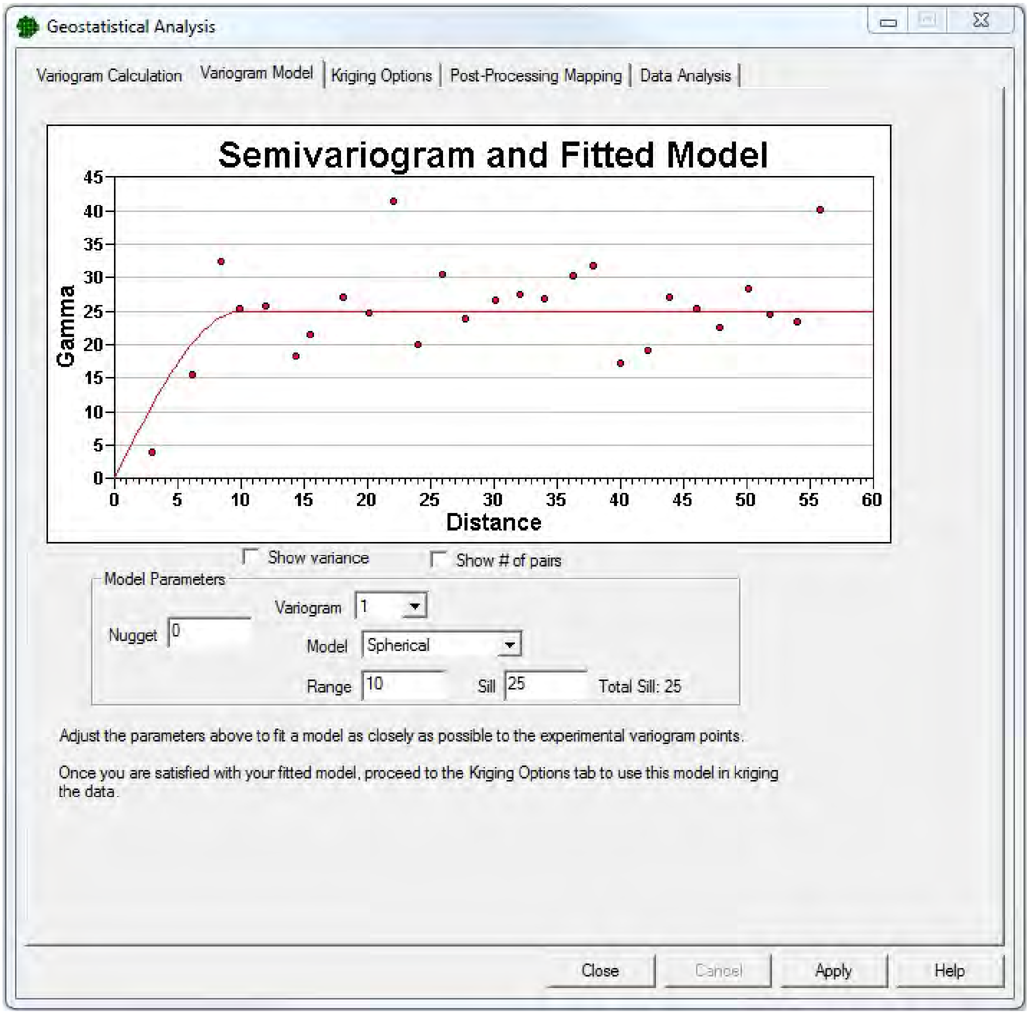

Figure C-1 Structural Analysis in VSP

Source: Matzke et al. 2014

Interpolation: VSP implements simple or ordinary kriging. It can also implement block kriging on a user-defined rectangular grid. VSP does not include universal kriging or co-kriging.

The user is able to specify an elliptical search neighborhood for interpolation. Among the controllable parameters of the search neighborhood are the major and minor axis lengths, the azimuth angle, and the maximum number of points within each quadrant. The search neighborhood can be designed to generate anisotropy.

Figure C-2 depicts the Post-Processing Mapping menu of VSP. The user can generate maps of the kriging estimate, kriging variance, percentiles, interquartile range, or probability of exceeding a concentration threshold. The maps can be saved to the report compiled by VSP.

VSP does not feature conditional simulation features.

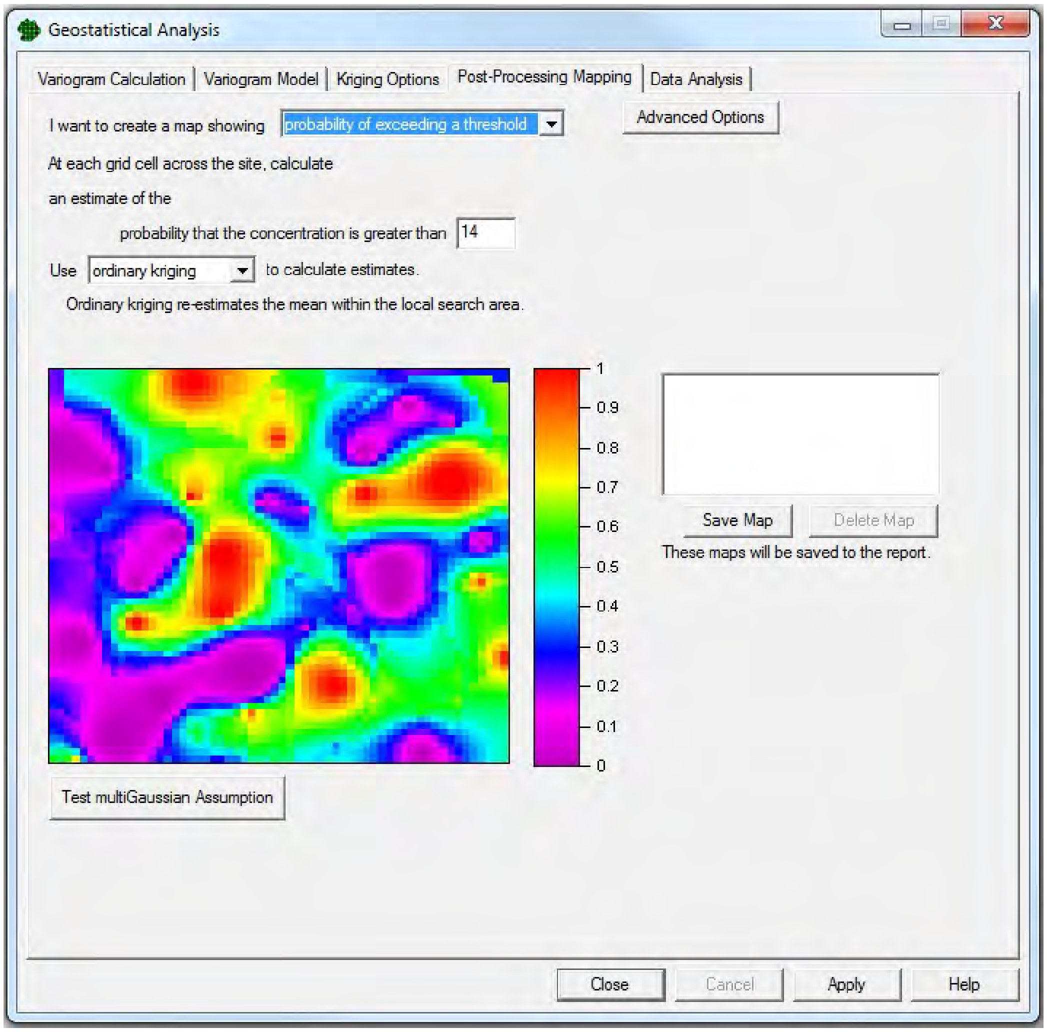

Figure C-2 Interpolation in VSP

Source: Matzke et al. 2014

Other Features: VSP[1] specializes in sample design. The software can generate sample plans for a multitude of different objectives: comparing average concentration to a fixed threshold (e.g., analysis described in NUREG-1575, "Multi-Agency Radiation Site Survey and Site Investigation Manual (MARSSIM)" (NRC 2000)), locating hot spots or discovering unacceptable areas with high confidence, detecting trends, assessing sample locations, among others. For each objective, the software recognizes different sample designs, including random, systematic, judgment, stratified, adaptive cluster, and sequential sampling. For each combination of objective and design, VSP guides the user through a questionnaire that reflects the planning approach sanctioned by the U.S. Environmental Protection Agency for data collection and decision making (i.e., the data quality objective process). This feature has been used to develop sampling maps for commercial power plant decommissioning projects.

Of the sampling objectives and designs, "assessing sample locations" and "sequential sampling" leverage geostatistics. In these cases, a geostatistical map is developed with existing data. Then, based on this map, sample location addition or removal can be assessed. Consider the

[1] VSP has absorbed many of the functionalities of COMPASS, the former NRC-sponsored software for conducting MARSSIM assessments.

example of assessing spatial redundancy of sample locations. Using the kriging prediction, VSP implements a method to generate a prediction for the added root-mean-squared error associated with the removal of each existing sample. By this method, sample locations can be ranked in terms of the cumulative importance of each well (see Figure C-3). This input can be vital in decision making.

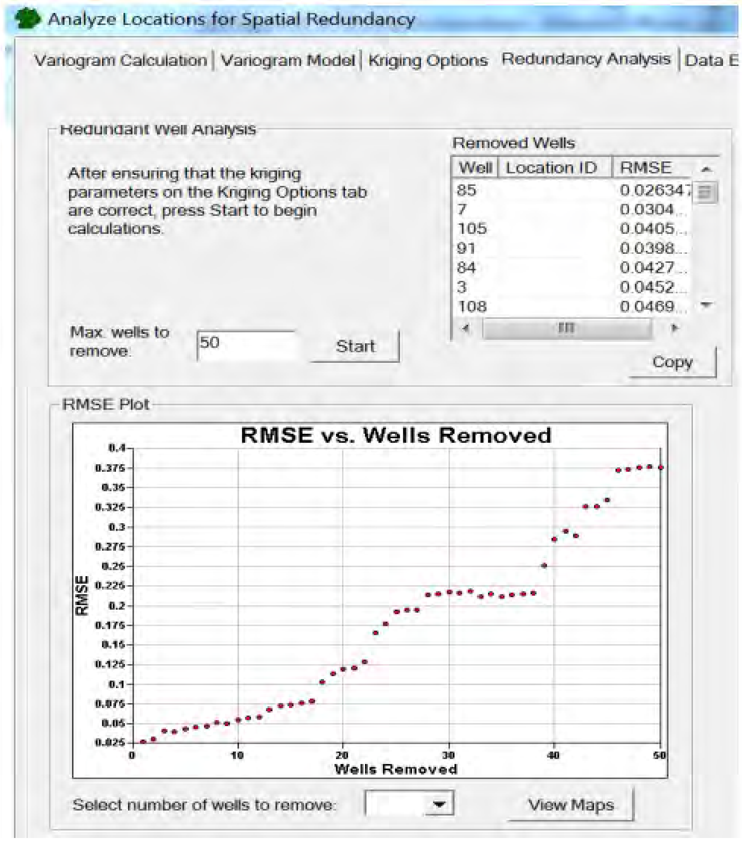

Figure C-3 Redundant Well Analysis in VSP

Source: Matzke et al. 2014

VSP also implements spatial-temporal kriging to support its assessment of temporal sampling redundancy. For this analysis, the user constructs a variogram with respect to time just as is done for spatial coordinates. Once complete, the spatial-temporal kriging model can be used to determine the optimal sampling interval. Spatial-temporal kriging is uncommon among standalone geostatistical software products.

Finally, the user can assign lump-sum and per-sample costs, allowing different strategies to be assessed within an economics context.

Accessibility: The most recent version of VSP (Version 7.5, submitted November 20, 2015) can be downloaded for free at http:/vsp.pnnl.gov. The software requires a Windows operating system. PNNP-23211, "Visual Sample Plan Version 7.0 User's Guide" (Matzke et al. 2014), is a user guide for the latest version of the software.

References:

Electric Power Research Institute (2016). "Guidance for Using Geostatistics in Developing a Site Final Status Survey Program for Plant Decommissioning," M.J. de Smith, M.F. Goodchild, and P.A. Longley, EPRI 3002007554, Palo Alto, CA, May 27, 2016. https://www.epri.com/research/products/3002007554

Matzke, B.D., J.E. Wilson, L.L. Newburn, S.T. Dowson, J.E. Hathaway, L.H. Sego, L.M. Bramer, and B.A. Pulsipher, "Visual Sample Plan Version 7.0 User's Guide," PNNL-23211, Pacific Northwest National Laboratory, Richland, WA, March 2014. https://vsp.pnnl.gov/docs/PNNL-23211.pdf

U.S. Nuclear Regulatory Commission (2000). "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)," NUREG 1575, Revision 1; EPA 402-R-97-016, Revision 1; DOE/EH 0624, Revision 1; U.S. Department of Defense; U.S. Department of Energy; U.S. Environmental Protection Agency; and U.S. NRC; Washington, DC, August 2000, ADAMS Accession No. ML003761445.

APPENDIX D

FITTING A VARIOGRAM

Figures

The experimental variogram for a particular separation vector of interest is calculated by averaging one-half the difference squared of the data values over all pairs of observations separated by approximately that vector. That is, given a set of n observed data: $\{(x_1, y_1, z_1),(x_2, y_2, z_2), \ldots (x_n, y_n, z_n)\}$, where (x_i, y_i) is the location of observation i, and z_i is the associated observed value. There are $n(n - 1)/2$ unique pairs of observations. For each of these pairs, the associated separation vector can be calculated.

What is usually referred to as “semivariogram cloud” is just a plot of half the squared differences versus the distances—that is, a scatterplot of the set of pairs $(h, \gamma(h))$ where:

$$h = ((x_i - x_j)^2 + (y_i - y_j)^2)^{1/2} \text{ and } \gamma(h) = 0.5\,(z_i - z_j)^2 \text{ and } i \neq j.$$

Figure D-1 shows that there is considerable scatter. To get an experimental variogram, the distances are grouped into bins that are located at multiples from 1 up to a specified maximum multiple of a lag distances, and a bin width of a specified lag tolerance, usually half the distance between lags. Some additional parameters are used in constructing the experimental variogram from the data. Most of these parameters relate to the formation of the data pairs used to calculate the spatial relationships. A variogram is a description of the spatial continuity of the data. The experimental variogram is a discrete function calculated using a measure of variability between pairs of points at various distances. The experimental variogram is calculated by averaging one-half the difference squared of the data values over all pairs of observations with a specified separation distance and direction.

The distances between pairs at which the variogram is calculated are called lags. For instance, lags may be calculated for samples that are a distance, h, apart. Then the lag is calculated for samples that are $2h$ apart, then $k \times h$ apart, and so on. Since points may not be spaced exactly h or $2h$ apart, the lag settings include a lag tolerance value that is typically set to half of the distance between lags, $0.5h$. Each point (red) plotted in Figure D-2 would represent the mean value of the variogram, $\gamma(h)$, for all pairs of points that are at a distance between $0.5h$ and $1.5h$ apart from each other. It is the value of the variogram (Y-axis) between pairs of points separated by the distance (X-axis) (i.e., half the squared differences in concentration at each pair of locations versus the distances between those locations).

Number of lags: Specifies how many lags of the variogram to calculate. This, together with the distance between lags, h, determines the maximum distance between pairs of points at which the variogram is calculated. This maximum distance is called the “variogram coverage” (number of lags times the distance between lags) and is displayed on the dialog. The variogram coverage should be less than the site size, and a good guideline is for the variogram coverage to be close to ½–¾ of the site size.

Distance between lags: The intervals to calculate lags. A good distance between lags should be no smaller than the shortest distance between data points and should be close to the average spacing of samples. The ideal lag spacing includes roughly the same number of pairs in each lag and at least 30 pairs for each lag.

Lag tolerance: How much the distance between pairs can differ from the exact lag distance and still be included in the lag calculations. The default is one-half of the distance between lags, which ensures that all possible pairs are included.

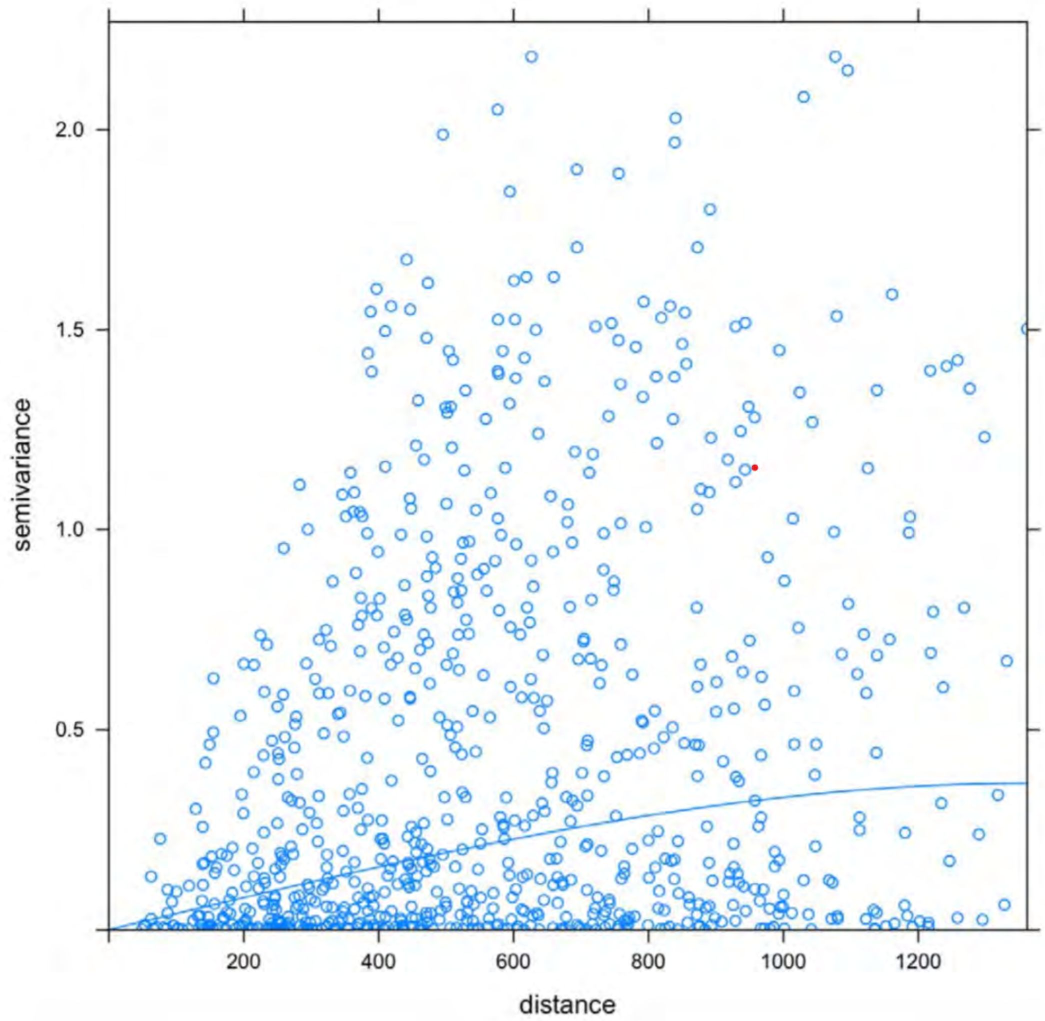

Figure D-1 Spherical Variogram Fit to Variogram Cloud Pairs (h, γ (h))

Source: Anselin 2016

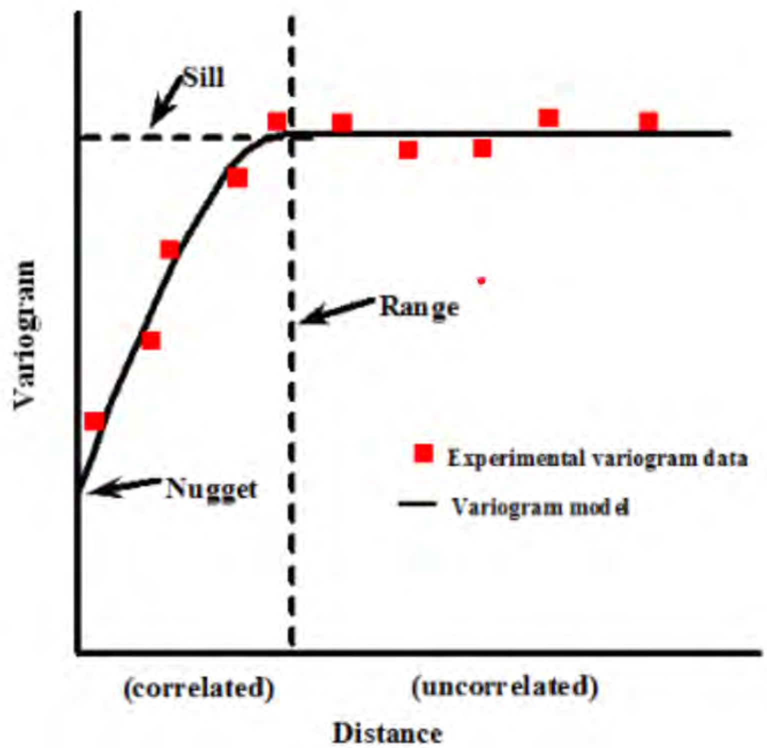

Figure D-2 An Example Variogram from Matzke et al. 2014
The distance is the lag distance (+/- the lag tolerance) separating pairs of locations where the concentration was measured.

The *range* is the distance after which the variogram levels off. The physical meaning of the range is that the concentration at pairs of points that are this distance or greater apart are not spatially correlated.

The *sill* is the total variance contribution, or the maximum variability between pairs of points. It represents how much the distance between pairs can differ from the exact lag distance and still be included in the lag calculations. The default is one-half of the distance between lags, which ensures that all possible pairs are included.

Nugget: Related to the amount of short-range variability in the data. Choose a value for the best fit with the first few empirical variogram points. A nugget that is large relative to the sill is problematic and could indicate too much noise and not enough spatial correlation. The nugget is sometimes interpreted to represent the analytical uncertainty in the concentration measurement, but that interpretation is not universally accepted. It can also be considered the variance due to "hot particles" being included in a sample (i.e., variance due to subsampling).

It is possible to estimate a fit to the variogram by choosing values for the nugget, sill, and range and specifying the exponential or spherical model.

The following is the formula of the spherical model:

$$\gamma(h) = \begin{cases} 0, & h = 0 \\ C_0 + C\left(\frac{3}{2}\frac{h}{a} - \frac{1}{2}\frac{h^3}{a^3}\right) & ,0 < h \leq a \\ C_0 + C & ,h > a \end{cases}$$

where C_0 is the nugget constant, $C + C_0$ is the sill, C is the structure variance, and a is the effective range. The slope rate at the point of origin is $3C/2a$, and the intersection between the sill value and x-axis is $2a/3$. The spherical model, shown in Figure D-3, is common in geostatistics.

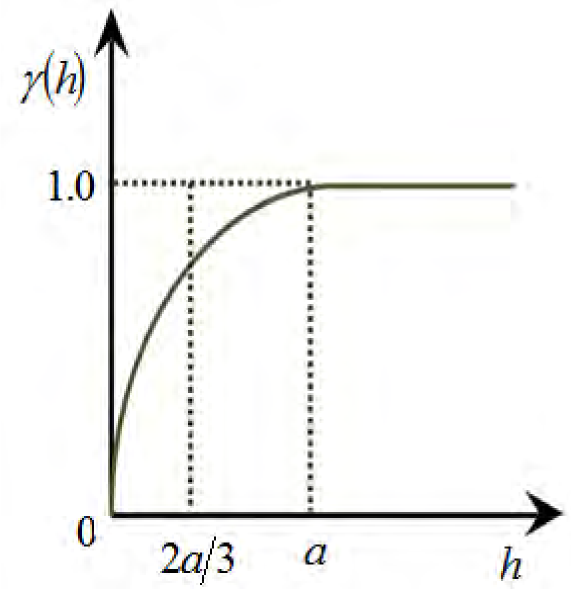

Figure D-3 Spherical Variogram Model

Source: Spatial Statistical Analyst 10.0 OnlineHelp
https://www.supergeotek.com/Spatial_Statistical_ENG_HTML/index.html?spherical_mode.htm

Compared with the spherical model, the exponential model has a linear growth in a short distance and then climbs with a very high slope. Finally, it reaches the sill value smoothly with a lower slope. The formula of the exponential model is as follows:

$$\gamma(h) = c * \left[1 - \exp\left(-\frac{(3h)^2}{a^2}\right)\right]$$

When $h = 3a$, $\gamma(h) \sim C + C_0$ and the effective range of the exponential model (Figure D-4) is $3a$.

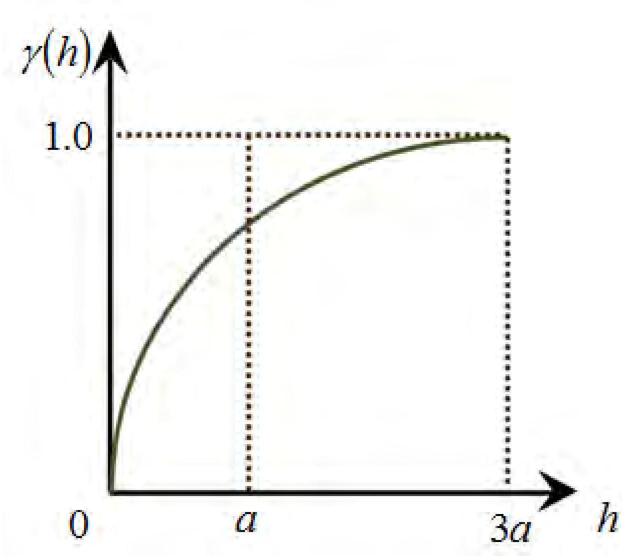

Figure D-4 Exponential Variogram Model

Source: Spatial Statistical Analyst 10.0 OnlineHelp
https://www.supergeotek.com/Spatial_Statistical_ENG_HTML/index.html?spherical_mode.htm

Max and min horizontal radii: These are the semi-major and semi-minor axes of the search ellipse, respectively. The *search ellipsoid* determines how far out to search for data to support a particular interpolated (kriged) estimate. If these axes are equal, the search ellipsoid is a circle. These axes should each be greater than the range of the variogram model and only if anisotropy is present. Changing the azimuth angle defining the orientation of the search ellipsoid is also necessary only for a site with anisotropy.

Grid size: Determines the resolution of the concentration estimate map. The ideal choice depends on the application and the data distribution, but it is important to ensure that the grid size is not too small relative to site size, since that would require a large number of estimates to be calculated and could result in a long execution time. About 20,000 grid points is a reasonable target.

Specifying these parameters is a complex task which requires some training and experience. The exact nomenclature for these parameters may vary, but the information needed is generally the same. However, both Visual Sampling Plan (VSP) and Spatial Analysis and Decision Assistance (SADA) provide an option for obtaining initial estimates of these parameters.

VSP does only two-dimensional geostatistical calculation, but the user's guide (Matzke et al. 2014) does contain a tutorial on the Variogram Calculation, Variogram Model, and Kriging Options steps in Section 3.2.10.1 of Chapter 3 (on sampling plan development within VSP), and Section 7.4 in Chapter 7 (on unexploded ordnance (UXO) site-related modules and features). Much of the discussion in these sections involves geostatistical modeling. An example is given of locating a new sample. This step takes the specified concentration of interest and places samples around areas close to that concentration to improve kriging estimates; however, there is no set procedure for specifying how many additional samples should be taken, nor the minimum spacing between the locations of each of the new samples. In the UXO module, the user is presented with two choices for computing the anomaly density map. In "Basic Mode," VSP will automatically compute a variogram and perform the kriging necessary to develop a spatial estimate of anomaly density. In this mode, a series of default values is computed for the data set and used in the variogram and kriging analyses. This mode is fully automatic and is recommended for new users. However, elsewhere the VSP guidance cautions against blindly using this feature.

SADA contains modules for both two-dimensional and three-dimensional geostatistics. These are covered in Part V of the SADA user's manual (Stewart et al. 2009), especially Chapters 29–31. Figure D-5 shows a dialog in SADA for entering parameters for creating and fitting a variogram. Some of these parameters have been defined above. This dialog can be quite daunting when first encountered. However, another way to begin, especially if one is relatively new to this, is to use the *Recommend* button. The *Recommend* button uses some basic rules of thumb to get you started. You should under no circumstances believe that these recommendations are optimal. Rather, they serve as a good starting point. SADA will try each model and determine which one is best according to a least-squares criterion *Graphical Edit* button. Two gray rectangles will appear, one at the origin and one near or at the range/sill point as shown in Figure D-6.

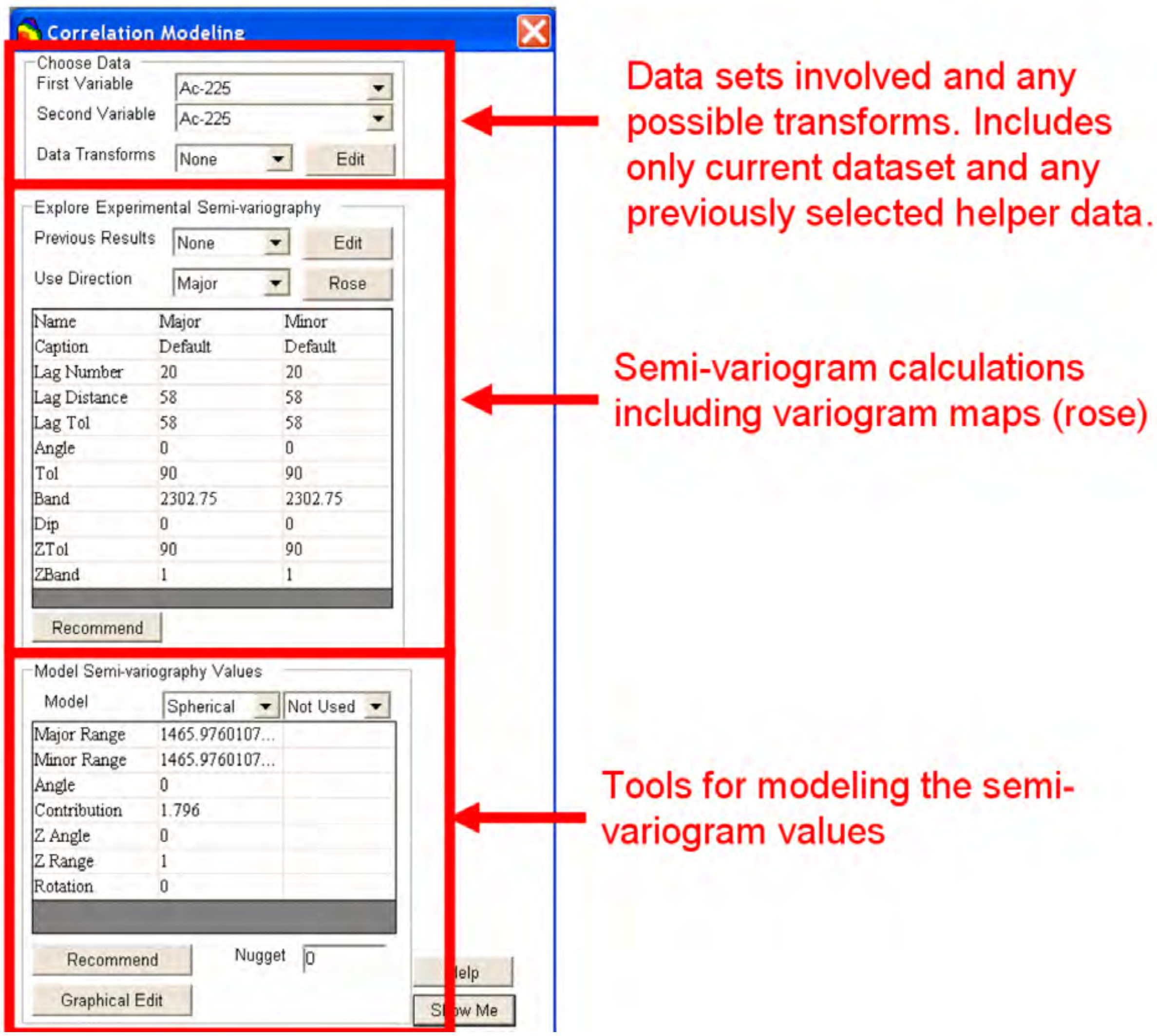

Figure D-5 Correlation Modeling in SADA

Source: Based on Stewart et al. 2009, p. 420

These issues are important because variography is central to kriging, and kriging is a key method used for interpolating data. It is also a key step in exploring locations to add samples to improve estimates. This would be one of the important goals coming out of the scoping survey and planning the characterization survey. NUREG-1575, “Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM),” Revision 1, Section 5.3, discusses characterization surveys in detail and concludes with a checklist of items to be addressed (NRC 2000). NUREG/CR-7021, “A Subsurface Decision Model for Supporting Environmental Compliance,” Chapter 7, issued January 2012 (NRC 2012), discusses the Characterization Phase and its relationship to refining the area of concern (AOC) map and the contamination concern map (CCM). The CCM is a spatially explicit, numerically defined implementation of a conceptual site model aimed at estimating activity level and concern for exceeding decision criteria at a very granular level. More specifically, it continuously maps, in three-dimensional space, the likelihood of contamination across the site. An AOC map is based on the CCM and indicates those regions that may require some remedial action. Based on the decision threshold, one can estimate where the boundaries of the AOC should be, given the data at hand and the latest CCM.

However, it may not be fruitful to spend much effort in calculating and fitting variograms. The experimental variogram itself is only an approximation to the actual covariance. Figure D-6 shows an experimental variogram fit to a spherical model. In spite of the scatter, this fit is actually reasonably good in the context of variogram modeling. The most important issue is to account for the spatial dependence between data points and the fact that this dependence decreases with distance. Values of the variogram at small distances result in the highest weight being given to points nearby where the interpolated value is sought. The smoothed contours of data values can generally be used to outline areas with contamination (areas of concern) and the probability of exceeding a derived concentration guideline level.

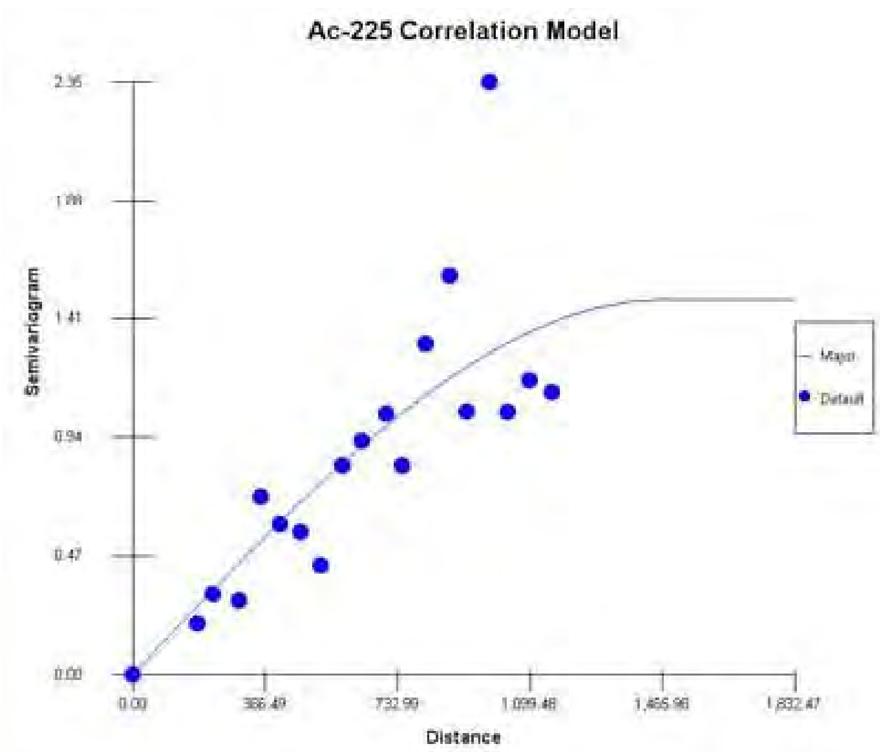

Figure D-6 Editable Variogram Example Fit in SADA

Source: Stewart et al. 2009, p. 338

References:

Anselin, Luc (2016). "Variogram," The Center for Spatial Data Science at the University of Chicago, 2016. https://spatial.uchicago.edu/sites/spatial.uchicago.edu/files/5_variogram_r.pdf

Matzke, B.D., J.E. Wilson, L.L. Newburn, S.T. Dowson, J.E. Hathaway, L.H. Sego, L.M. Bramer, and B.A. Pulsipher, "Visual Sample Plan Version 7.0 User's Guide," PNNL-23211, Pacific Northwest National Laboratory, Richland, WA, March 2014. https://vsp.pnnl.gov/docs/PNNL-23211.pdf

Stewart, R., Welsh, C., Purucker, T., and Stewart, D. (2009). "An Introduction to Spatial Analysis and Decision Assistance (SADA), Environmental Applications for Version 5, User Guide," University of Tennessee, Knoxville, TN, December 19, 2009. https://www.sadaproject.net/documentation.html

U.S. Nuclear Regulatory Commission (2000). "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)," NUREG-1575, Revision 1; EPA 402-R-97-016, Revision 1; DOE/EH 0624, Revision 1; U.S. Department of Defense; U.S. Department of Energy; U.S. Environmental Protection Agency; and U.S. NRC; Washington, DC, August 2000, ADAMS Accession No. ML003761445.

— — — (2012). "A Subsurface Decision Model for Supporting Environmental Compliance," NUREG/CR-7021, prepared by University of Tennessee, Knoxville, TN, for NRC Office of Nuclear Regulatory Research, Washington, DC, January 2012.

APPENDIX E

SURVEY DESIGNS IN VSP AND SADA

The Spatial Analysis and Decision Assistance (SADA) user's guide, Part VII, Chapters 37–41,[1] covers survey designs of several types:

Part VII: Sample Design

Chapter 37: Overview of Sample Designs
- Determining Number of Samples
- Number of Samples for Sign Test
- Number of Samples for Wilcoxon Rank Sum Test
- You Pick (User Specified)
- Sample Placement: 2d, 3d, and Core
- Minimum Distance Constraint
- Tie Breakers
- Ghost Samples (visualization)
- Polygons and Vertical Layers

Chapter 38: Secondary Sampling Designs
- Judgmental Design
- Threshold Radial
- Adaptive Fill Design
- Ripley's K
- Moran's I
- Geary's C
- High Value
- Area of Concern
- Stored Results

Chapter 39: Standard Initial Sampling Designs
- Judgmental Designs
- Simple Random
- Simple Grid and Simple Grid (unaligned)
- Standard Grids and Standard Unaligned Grids
- MARSSIM Design
- Hot Spot Searches
- 3d Hot Spot Search
- Stored Sample Designs
- Hotspot Search References

Chapter 40: Multi-Agency Radiation Survey and Site Investigation Manual (Scenario A)
- Survey Unit
- Release Criterion
- Classifying the Survey Unit
- MARSSIM Sample Designs in SADA
- Class I/II Example
- Class III Example
- Part II: Analysis of Data

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1 Stewart, R., Welsh, C., Purucker, T., and Stewart, D. (2009). "An Introduction to Spatial Analysis and Decision Assistance (SADA), Environmental Applications for Version 5, User Guide," University of Tennessee, Knoxville, TN, December 19, 2009. https://www.sadaproject.net/documentation.html

Setting up the MARSSIM Analysis
Determining Compliance
A Class I/II Example
Class III Example (with WRS)
Connecting Geospatial Decision Analysis and MARSSIM
MARSSIM Quick Tools
Chapter 41: Informed and Targeted Initial Designs
Sources of Prior Knowledge
Targeted High Value Design (simple)
Area of Concern Design (simple)
Target High Value and Area of Concern Design (non-simple)
Bayesian Ellipgrid
Check and Cover Sample Design
Determining Number of Samples

The Visual Sample Plan (VSP) user's guide, Chapter 3,[2] covers sampling plan development within VSP:

3.1 Sampling Plan Type Selection
3.1.1 Defining the Purpose/Goal of Sampling
3.1.2 Selecting a Sampling Design
3.2 DQO Inputs and Sample Size
3.2.1 Compare Average to a Fixed Threshold
3.2.2 Compare Average to Reference Average
3.2.3 Estimate the Mean
3.2.4 Construct Confidence Interval on Mean
3.2.5 Locating a Hot Spot
3.2.6 Show That At Least Some High % of the Sampling Area is Acceptable
3.2.7 Discover Unacceptable Areas with High Confidence
3.2.8 Combined Average and Individual Measurement Criteria
3.2.9 Detecting a Trend
3.2.10 Identify Sampling Redundancy
3.2.11 Add Sampling Locations
3.2.12 Compare Proportion to Fixed Threshold
3.2.13 Compare Proportion to Reference Proportion
3.2.14 Construct Confidence Interval on Proportion
3.2.15 Estimate the Proportion
3.2.16 Establish Boundary of Contamination
3.2.17 UXO Guide
3.2.18 Find UXO Target Areas
3.2.19 Post Remediation Verification Sampling
3.2.20 Remedial Investigation
3.2.21 Sampling Within Buildings
3.2.22 Radiological Transect Surveying
3.2.23 Item Sampling
3.2.24 Non-statistical Sampling Approach
3.2.25 Last Design

2 Matzke, B.D., J.E. Wilson, L.L. Newburn, S.T. Dowson, J.E. Hathaway, L.H. Sego, L.M. Bramer, and B.A. Pulsipher (2014). "Visual Sample Plan Version 7.0 User's Guide," PNNL 23211, Pacific Northwest National Laboratory, Richland, WA, March 2014. https://vsp.pnnl.gov/docs/PNNL-23211.pdf

APPENDIX F

EXAMPLES OF ALTERNATIVES TO MARSSIM STATISTICAL TESTS

Table F-1 Examples of Alternate Statistical Tests

Alternate Tests	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Alternate 1—Sample Tests (No Reference Area Measurements)					
Student's *t* Test	Normal	Parametric test for H_0: Mean < t	*Guidance for Data Quality Assessment*, EPA QA/G-9, p. 3.2-2.	Appropriate if data appear to be normally distributed and symmetric.	Relies on a nonrobust estimator for μ and σ. Sensitive to outliers and departures from normality.
***t* Test Applied to Logarithms**	Lognormal	Parametric test for H_0: Median < t	*Guidance for Data Quality Assessment*, EPA QA/G-9, p. 3.2-2.	A well-known and easy-to-apply test. Useful for a quick summary of the situation if the data are skewed to right.	Relies on a nonrobust estimator for σ. Sensitive to outliers and departures from lognormality.
Minimum Variance Unbiased Estimator for Lognormal Mean	Lognormal	Parametric estimates for mean and variance of lognormal distribution	Gilbert, *Statistical Methods for Environmental Pollution Monitoring*, p. 164, 1987.	A good parametric test to use if the data are lognormal.	Inappropriate if the data are not lognormal.
Chen Test	Skewed to right, including logormal	Parametric test for H_0: Mean > 0	Chen, *Journal of the American Statistical Association (90)*, p. 767, 1995.	A good parametric test to use if the data are lognormal.	Applicable only for testing H_0: "survey unit is clean." Survey unit must be significantly greater than 0 to fail. Inappropriate if the data are not skewed to higher values.
Bayesian Approaches	Varies, but a family of probability distributions must be selected	Parametric test for H_0: Mean < L	DeGroot, *Optimal Statistical Decisions*, 2005.	Permits use of subjective "expert judgment" in interpretation of data.	Decisions based on expert judgment may be difficult to explain and defend.
Bootstrap	No restriction	Nonparametric; uses resampling methods to estimate sampling variance	Hall, *Annals of Statistics (22)*, p. 2011–2030, 1994.	Avoids assumptions concerning the type of distribution.	Computer-intensive analysis required. Accuracy of the results can be difficult to assess.
Lognormal Confidence Intervals Using Bootstrap	Lognormal	Uses resampling methods to estimate one-sided confidence interval for lognormal mean	Angus, *The Statistician (43)*, p. 395, 1994	Nonparametric method applied within a parametric lognormal model.	Computer-intensive analysis required. Accuracy of the results can be difficult to assess.

Alternate Tests	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Alternate 2—Sample Tests (Reference Area Measurements Are Required)					
Student's *t* test	Symmetric, normal	Parametric test for difference in means H_0: $\mu_x < \mu_y$	*Guidance for Data Quality Assessment*, EPA QA/G-9, p. 3.3-2.	Easy to apply. Performance for nonnormal data is acceptable.	Relies on a nonrobust estimator for σ; therefore, test results are sensitive to outliers.
Mann-Whitney Test	No restrictions	Nonparametric test difference in location H_0: $\mu_x < \mu_y$	Hollander, *Nonparametric Statistical Methods*, 2014.	Equivalent to the WRS test but used less often. Similar to resampling, because test is based on set of all possible differences between the two data sets.	Assumes that the only difference between the test and reference areas is a shift in location.
Kolmogorov-Smirnov	No restrictions	Nonparametric test for any difference between the two distributions	Hollander, *Nonparametric Statistical Methods*, 2014.	A robust test for equality of two sample distributions against all alternatives.	May reject because variance is high, although mean is in compliance.
Bayesian Approaches	Varies, but a family of probability distributions must be selected	Parametric tests for difference in means or difference in variance	Box and Tiao, *Bayesian Inference in Statistical Analysis*, 2011.	Permits use of "expert judgment" in the interpretation of data.	Decisions based on expert judgment may be difficult to explain and defend.
2-Sample Quantile Test	No restrictions	Nonparametric test for difference in shape and location	EPA, *Methods for Evaluating the Attainment of Cleanup Standards*, *Vol. 3*, p. 7.1, 1994.	Will detect if survey unit distribution exceeds reference distribution in the upper quantiles.	Applicable only for testing H_0: "survey unit is clean." Survey unit must be significantly greater than 0 to fail.
Sign Test when Background is Present	No restrictions	Nonparametric test for difference in location assuming uniform background	Abelquist, *Decommissioning Health Physics: A Handbook for MARSSIM Users*, 2nd Edition, 2014.	Less computationally intensive. Consistent with pre-MARSSIM survey designs.	Less powerful than the Wilcoxon Rank Sum Test because of assumptions concerning background distributions.
Bootstrap and Other Resampling Methods	No restrictions	Nonparametric; uses resampling methods to estimate sampling variance	Hall, *Annals of Statistics (22)*, p. 2011, 1994.	Avoids assumptions concerning the type of distribution. Generates informative resampling distributions for graphing.	Computer-intensive analysis required.
Alternate to Statistical Tests					
Decision Theory	No restrictions	Incorporates loss function in the decision theory approach	DOE, *Statistical and Cost-Benefit Enhancements to the DQO Process for Characterization Decisions*, 1996.	Combines elements of cost-benefit analysis and risk assessment into the planning process.	Limited experience in applying the method to compliance demonstration and decommissioning. Computer-intensive analysis required.

Source: NUREG-1575, Revision 2, "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)," draft Revision 2, Chapter 2.6, Section 2.6.1, Table 2.3, issued May 2020 (NRC 2020b)

APPENDIX G

NATURAL BACKGROUND

Table of Contents

Figure

Tables

G.1 Natural Background

Background is 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. Figure G-1 below shows how the concentrations of just uranium in the ground vary across North America.

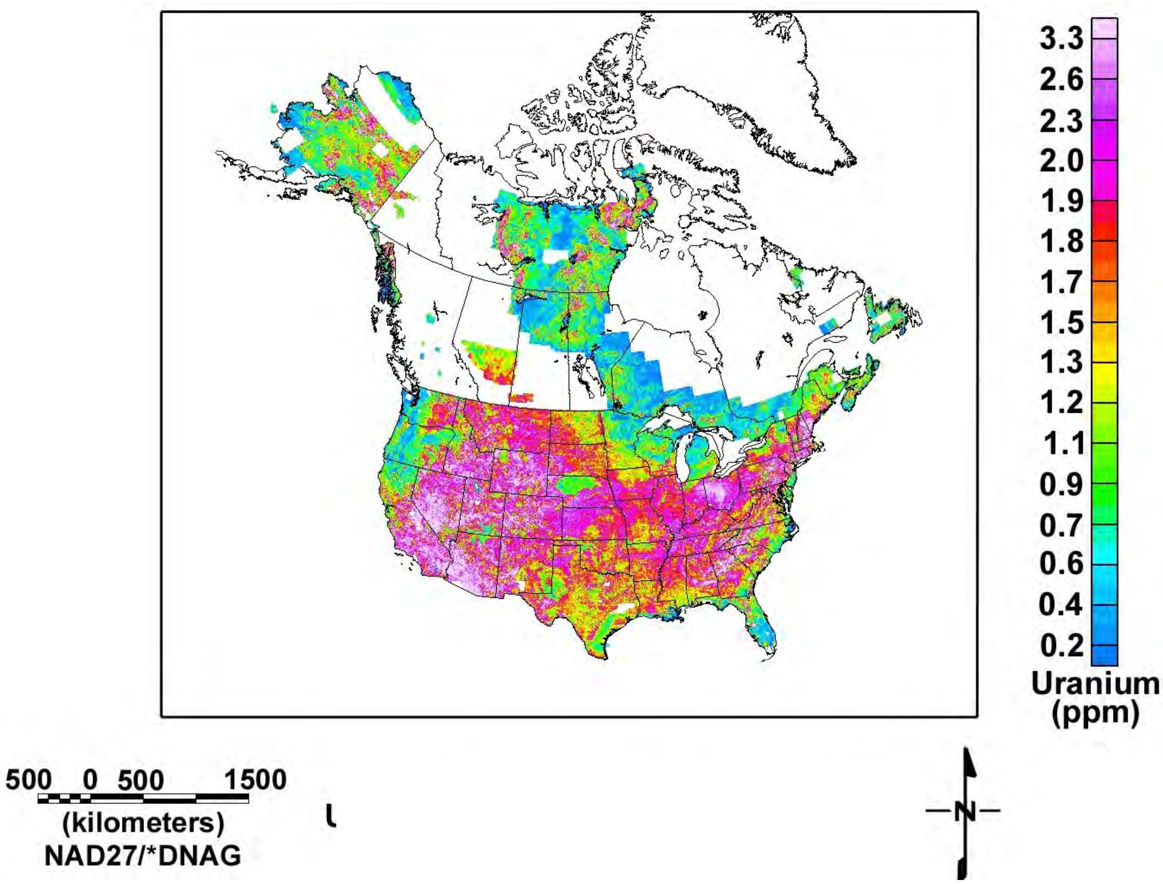

Figure G-1 Uranium Concentrations

Source: U.S. Geological Survey Open File Report
https://pubs.usgs.gov/of/2005/1413/maps.htm

- Terrestrial radiation is radiation from naturally occurring radionuclides in the soil, which include potassium (K)-40, thorium (Th)-232, uranium (U)-238, rubidium (Rb)-87, and U-235 and their progeny.

- Radon (Rn-222) is a radioactive gas produced from the decay of radium (Ra)-226, which is a member of the U-238 decay chain. Dose from radon is not usually included in the release criterion, but radon consideration may be required for restricted release.

- Both tritium (H-3) and strontium (Sr)-90 and cesium (Cs)-137 are in background from nuclear weapons testing, nuclear accidents, and radioactive releases from nuclear power plants into the environment.

The potential for residual radioactivity can come from use of source, byproduct, and special nuclear materials as well as naturally occurring radioactive material (NORM), naturally occurring and accelerator-produced radioactive materials (NARM), and technologically enhanced naturally occurring radioactive material (TENORM). This material may be related to commercial, research, education, or defense uses. The material might be (NRC 2009)—

- used or stored at sites and facilities licensed to handle radioactivity
- commercial products purposely containing radionuclides (e.g., smoke detectors)
- commercial products incidentally containing radionuclides (e.g., phosphate fertilizers) or
- associated with NORM and TENORM

G.2 Regulatory Considerations

The release criteria in Title 10 of the *Code of Federal Regulations* (10 CFR) 20.1402, "Radiological criteria for unrestricted use," and 10 CFR 20.1403, "Criteria for license termination under restricted conditions," specify a total effective dose limit due to residual radioactivity that is *distinguishable from background radiation.* According to 10 CFR 20.1003, "Definitions," *background radiation* means radiation from cosmic sources; NORM, including radon (except as a decay product of source or special nuclear material); and global fallout as it exists in the environment from the testing of nuclear explosive devices or from nuclear accidents like Chernobyl, which contribute to background radiation and are not under the control of the licensee. Background radiation does not include radiation from source, byproduct, or special nuclear materials regulated by the Commission. The term *distinguishable from background* means that the detectable concentration of a radionuclide is statistically different from the background concentration of that radionuclide in the vicinity of the site, or, in the case of structures, in similar materials using adequate measurement technology, survey, and statistical techniques (NRC 1998).

Two approaches were initially considered for applying background as a decommissioning criterion; these are the use of background dose rates and background radionuclide concentrations. NUREG-1501, "Background as a Residual Radioactivity Criterion for Decommissioning: Appendix A to the Draft Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC-Licensed Nuclear Facilities—Draft Report for Comment," issued August 1994 (NRC 1994), concluded that the temporal and spatial variability of background produces a wide range of doses to U.S. residents, which prevents the application of background dose rates as a decommissioning criterion. Instead, local background radionuclide concentrations are recommended for use as a benchmark for decommissioning criteria, while considering the concept of reducing residual radioactivity to as low as reasonably achievable (NRC 1994).

G.3 Survey Design Considerations

For the purposes of survey design, the method of accounting for background radiation will depend not only on the radionuclides involved, but also on the type of measurements made. For radionuclide-specific measurements of radionuclides that do not appear in natural background, it is clear that no adjustments for background are needed. In some cases, a sample-specific background adjustment may be possible. For example, residual U-238 activity may be distinguishable from natural U-238 by the amount of Ra-226 present in a sample. In other cases, it will not be possible to make such a distinction. In particular, such a distinction will not be possible, even if the radionuclide does not appear in background, when gross activity or exposure rate measurements are used (NRC 1998).

When a specific background[1] can be established for individual samples, the results of the survey unit measurements can be compared directly to the derived concentration guideline level (DCGL), since each is a measurement of the residual radioactivity alone. For example, if two radionuclides appear in a specific environmental media, in a commonly fixed ratio, any significant deviation from this ratio may be attributable to facility operations. The background for the radionuclide of concern can be established for each sample using the established ratio. Because only one set of measurements is involved in this comparison, the statistical test is called a *one-sample test* (NRC 1998).

When a specific background cannot be established for individual samples, the survey unit measurements cannot be directly compared to the DCGL, since each is a measurement of the total of any residual radioactivity plus the survey unit background. In this case, the measurements in a survey unit must be compared to similar measurements in local *reference areas* that have been matched to the survey unit in terms of geological, chemical, and biological attributes, but that have not been affected by site operations. The distribution of the measurements in a survey unit is compared to the distribution of background measurements in a reference area. Because two sets of measurements are used in making this comparison, the statistical test is called a *two-sample test* (NRC 1998).

If the contaminant is part of NORM, reference (background) samples are collected at random locations in background reference areas. Background concentrations are determined from measurements in soil samples taken at one or more nearby offsite locations where contamination is highly unlikely. The sensitivity of the instruments used must comply with the specified data quality objectives for the survey. As stated in NUREG-1575, Revision 1, “Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM),” issued August 2000 (NRC 2000), the number of background measurements should equal those taken in any survey unit in a contaminated zone; one background sampling campaign is sufficient to support all survey units.

G.4 Selection of Background Reference Areas

Establishing background concentrations that describe a distribution of measurement data is necessary to identify and evaluate contributions attributable to site operations. Determining background levels for comparison with the conditions determined in specific survey units may entail conducting surveys in one or more reference areas to define the radiological conditions of the site. NUREG-1505, Revision 1, “A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys—Interim Draft Report for Comment and Use,” issued June 1998 (NRC 1998), provides additional information on background reference areas.

The *background reference area* is a geographical area from which representative reference measurements are performed for comparison with measurements performed in specific survey units. If the radionuclide of concern is present in the background, or if the measurement system used to determine concentration in the survey unit is not radionuclide specific, background measurements are compared to the survey unit measurements to determine the concentration of residual radioactive material. The 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 has not been affected by site activities (i.e., nonimpacted) (NRC 2000).

[1] Specific background may be application of a specific material measurement (gross or radionuclide specific) of concrete or other material such as steel, aluminum, or granite.

This may require offsite surveying, and Maine Yankee Atomic Power Company committed to using offsite areas as the background reference area (Acker 2005).

Reference areas provide a location for background measurements, which are used for comparisons with survey unit data. The radioactivity in a reference area would ideally be the same as that in the survey unit had it never been contaminated. If a site includes physical, chemical, geological, radiological, or biological variability that is not represented by a single reference background area, selecting more than one reference area may be necessary (NRC 2000).

It may be difficult to find a reference area within an industrial complex for comparison to a survey unit if the radionuclides of potential concern are naturally occurring. Background may vary greatly because of different construction activities that have occurred at the site. Examples of construction activities that change background include leveling; excavating; adding fill dirt; importing rocks or gravel to stabilize soil or underlay asphalt; manufacturing asphalt with different matrix rock; using different pours of asphalt or concrete in a single survey unit; layering asphalt over concrete; layering different thicknesses of asphalt, concrete, rock, or gravel; and covering or burying old features such as railroad beds or building footings. Background variability may also increase because of the concentration of fallout in low areas of parking lots where runoff water collects and evaporates. Variations in background of a factor of 5 or more can occur in the space of a few hectares (NRC 2000).

Reference soil-like material for a site background reference area should have physical, chemical, geological, radiological, and biological characteristics similar to those of the soil-like material being evaluated. Background reference areas are normally selected from nonimpacted areas but are not limited to natural areas undisturbed by human activities (NRC 2000).

G.5 Background Suite of Radionuclides

As indicated in MARSSIM, certain radionuclides may also occur at significant levels as part of background in the media of interest (for example, soil, soil-like material, concrete). Examples include members of the naturally occurring uranium, thorium, and actinium series; K-40; carbon (C)-14; and tritium. Cs-137 and other radionuclides are also present in background as a result of nuclear weapons fallout (Wallo et al. 1994; NRC 2000). Tables G-1 and G-2 contain data on the activities and concentrations of some NORM. Information in Table G-2 may be of interest to show the natural ratios for comparison to potential enrichment.

Table G-1 Levels in the Environment[a]

Radionuclide	Environment Level
Cs-137	The concentration of Cs-137 in surface soil from fallout ranges from about 0.1 to 1 picocurie per gram (pCi/g), averaging less than 0.4 pCi/g.
H-3	Tritium is naturally present in surface waters at about 10 to 30 pCi/liter (L). The maximum contaminant level developed by the U.S. Environmental Protection Agency (EPA) for tritium in drinking water supplies is 20,000 pCi/L.
K-40	Because potassium-40 represents 0.012% of naturally occurring potassium, its concentration in the earth's crust is about 13 pCi/g.

Radionuclide	Environment Level
Natural Uranium	Uranium is a naturally occurring radioactive metal in all rocks and soils in low concentrations (1 to several hundred pCi/g) (ANL 2007) A square kilometer of earth, 30 centimeters deep, will typically contain a ton or more of uranium (HPS 2018). The average concentration of uranium in the ground water of the United States is about 1.9 pCi/L. The EPA's drinking-water standard for uranium is 30 micrograms per liter (µg/L), which is about 20 pCi/L (EPA 2001).
Ra-226	Essentially all naturally occurring radium is present as Ra-226. Radium exists naturally in soil, rocks, surface water, ground water, plants, and animals in generally low concentrations—on the order of one part per trillion, or 1 pCi/g. Higher levels are present in uranium ores and other geologic materials.

[a] Progeny of primary radionuclides would be included.

Sources: ANL 2007; EPA 2001, EPA 2006, and HPS 2018

A recent study by the U.S. Geological Survey of lead (Pb)-210 and polonium (Po)-210 in drinking-water supplies may pose human health concerns. Pb-210 and Po-210 were detected in groundwater samples from 1,263 public-supply wells in 19 principal aquifers across the United States (Szabo et al. 2020). This is not yet in the EPA list of maximum contaminant levels (Table 2-3 of the white paper) but may be important in the future.

Table G-2 Mass and Activity Abundances of Naturally Occurring Isotopes in Chemically Separated Uranium and Thorium

Element	Isotope	Half-life (y)[a]	Mass Abundance	Activity Abundance
Uranium (natural)	U-238	4.468×10^{9}	99.28%[b]	48.9%[c]
	U-235	7.038×10^{8}	0.72%	2.2%
	U-234	2.455×10^{5}	0.006%	48.9%
Uranium (depleted)	U-238	4.468×10^{9}	99.8%[d]	90.1%[e]
	U-235	7.038×10^{8}	0.2%	1.50%
	U-234	2.455×10^{5}	0.001%	8.40%
Thorium	Th-232	1.405×10^{10}	100%	50%[f]
	Th-228	1.9132		50%

Source: NRC 2001

[a] Values from Kocher (1981).

[b] Mass abundances for isotopes in natural uranium (EPA 2006).

[c] Activity abundances for isotopes in natural uranium are based on known mass abundances and half-lives and assumption that U-238 and U-234 occur in equal activity abundances (EPA 2006)

[d] Mass abundances for isotopes in depleted uranium obtained as byproduct residues from uranium enrichment reported (EPA 2006).

[e] Activity abundances for isotopes in depleted uranium are based on assumed mass abundances and known half-lives (EPA 2006).

[f] Activity abundances for isotopes in natural thorium are based on assumption of equal activity abundances of Th-232 and Th-228 at time of chemical separation and assumption that no other isotopes of thorium produced in decay of naturally occurring isotopes of uranium are present (NRC 2001).

G.6 References

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APPENDIX H

SELECTED SUBSURFACE SOIL REMEDIATION CASES

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Figures

Table

This appendix describes two example sites as case studies to provide context for the types of problems faced by licensees and reviewers in surveying and analyzing final status survey (FSS) data for subsurface residual radioactivity. The appendix lists several others, along with relevant references, and summarizes approaches used and in some cases lessons learned from review of licensees submittals. In many cases, the FSS has not yet been approved, and discussion of proposed approaches should not be taken as U.S. Nuclear Regulatory Commission (NRC) approval of the proposals.

H.1 AAR Manufacturing Group, Inc.

Livonia, MI
License No.: STB-0362 (terminated)
Docket No.: 04000235

Slag from processing thorium ore to produce ingots disposed of on site. Part of license termination review project (nonlicensee required to clean up site).

Multiple Sets of Derived Concentration Guideline Levels (DCGLs): Surface (0 to 1 meter (m)) subsurface (1–2 m)

While historical and never actually used, it is important to note that in 1997 the U.S. Nuclear Regulatory Commission (NRC) developed for AAR Manufacturing Group, Inc. (AAR), a method for surveying and averaging concentrations of thorium in contaminated subsurface soil (NRC 1997). Simple scenarios were developed to predict how subsurface soil would be excavated in the future, the volume of excavated soil, and the dose consequences of the contaminated soil in the postexcavation geometry. Two excavation scenarios were evaluated. The first scenario assumes the construction of a slab-on-grade house; the second a house with a basement. For each of the construction scenarios, the volume of excavated soil, the extent of surface spreading, and the depth of surfaces on which the foundations could be built were estimated. The potential dose from the subsurface soil, after excavation, was estimated by (1) calculating the dose from the contaminated soil spread on the ground surface and (2) calculating the dose from the in situ contaminated surface that is exposed after excavation, assuming that the foundation of the house is built on the exposed surface. More details appear in NRC (1997), with cautions on potential dose from the water pathway. Based on the predicted excavation volumes and the dose consequences, surveying and averaging protocols were developed for in situ subsurface soil, as shown in Table H-1.

The volumetric average over the entire survey unit was to be less than the unrestricted use limit at the time of 10 picocuries per gram (pCi/g) for total thorium. The averaging criteria were applied to contiguous volumes defined by the given number of grid samples, where each sample represented 25 m^3, and specific instructions were provided for averaging volumes over 100 m^3.

In addition to the above, a vertical averaging criterion was defined to identify significant volumes of contiguous contamination in the vertical, as opposed to the horizontal, direction. The sampling and averaging criteria below also assumed a 5-m grid size:

- The average of the two samples from 0–2 m in the same borehole (50 m^3) is less than 1 pCi/g total thorium.
- The average of the three samples from 0–3 meters in the same borehole (75 m^3) is less than 13 pCi/g total thorium.

Table H-1 Averaging Criteria for Total Thorium (Th-232 + Th-228)

Depth	Maximum Individual Sample
0–1 meter depth	Maximum < 50 pCi/g 10 m^3 average < 20 pCi/g 100 m^3 average < 13 pCi/g
1–2 meter depth	Maximum < 50 pCi/g 200 m^3 (0–2 m depth) < 10 pCi/g
2–3 meter depth	Maximum < 50 pCi/g 300 m^3 (0–3 m depth) < 10 pCi/g
3–4 meter depth	Maximum < 50 pCi/g 100 m^3 average < 13 pCi/g 400 m^3 (0–4 m depth) < 10 pCi/g
>4 m depth	Maximum < 50 pCi/g Volume from surface to depth “x” < 10 pCi/g

Source: NRC 1997

More recent dose modeling considered the spatial variability in concentrations from the 0–1 m and 1–2 m intervals and applied site- and radionuclide-specific external gamma shielding factors in dose assessments (Barr and Schmidt 2009). Geostatistical tools in GMS were used to analyze the data (see Figure H-1). The NRC staff performed independent analysis using Spatial Analysis and Decision Assistance (SADA) to determine uncertainty in exposure area concentrations for exposure areas of various sizes, including smaller areas that would constitute “elevated areas” (see Figures H-2 through H-4) to conclude that the site was acceptable for release (low likelihood of doses above the release criteria). Compliance uncertainty and the risk of elevated areas were evaluated using this approach. Site-specific dose modeling was performed based on final survey data to estimate the dose based on the final configuration of residual radioactivity at the site. MCNP (Monte Carlo N-Particle) modeling and site-specific information about home construction were used to support the development of external gamma shielding factors, including consideration of a basement receptor.

Scenarios/Initiating Events: Resident Gardener (compliance scenario)
Industrial (additional scenario for information)
Recreational Receptor (additional scenario for information)

***Codes Used*:** RESRAD
Groundwater Modeling System (GMS) (geostatistical tools)
Spatial Analysis and Decision Assistance (SADA) (geospatial analysis)
MicroShield

The NRC’s review included use of MCNPX (Monte Carlo N-Particle Transport Code Extended) (LANL 2005) modeling, which is expected to significantly reduce the uncertainty in the risk calculations. MicroShield software (Grove 2008) was also used in shielding calculations.

Excavation or Soil Removal: Residual radioactivity at the AAR site occurs to a depth of 2 m, and the conceptual model for dose assessment has split the soil into two layers: 0–1 m and 1–2 m. The site was characterized based on units of 100 m^2 (i.e., 10 m by 10 m) grids.

Reused Soils: Backfilled with clean[1] gravel.

[1] “Clean” throughout this appendix means free of residual radioactivity.

Dose Modeling and Survey Notes: The external dose and plant ingestion dominate the dose. After review of the literature on radium plant transfer factors, the plant ingestion pathway is considered less important. The ground water pathway was eliminated.

The western parcel of the site originally slated for restricted release (later released for unrestricted use) is covered with vegetation, and so it is expected that significant earth-moving activities would be needed to develop that section of the site allowing for some mixing of soils. Relatively small hot spots are less of a concern for the site because of the averaging of time on any portion of the site (external dose dominates the dose); however, additional scenarios and analyses were used to evaluate the risk associated with elevated areas. Additionally, SADA was used in independent analysis to determine the significance of exposure area variability on dose for a range of exposure areas.

Thirty-two 100 m^2 areas were targeted for removal. If the concentration in the exposed 1–2 m interval exceeded the 1–2 m cleanup level of 20 picocuries per gram (pCi/g) total thorium, then the 1–2 m interval would also be removed. Four samples were taken in each 100 m^2 area to calculate the average for the interval.

Approach to Surveying of Excess or Survey of Used Soils: 32 grids excavated and filled with clean fill.

The bottom of the excavation was surveyed to ensure that cleanup criteria were met. In two cases, AAR removed the 1–2 m interval when not planned (based on sampling data that suggested higher than expected concentrations in the 1–2 m interval). This was to ensure that the average concentration in the 1–2 m interval met the cleanup criteria.

Materials were sent to a disposal facility under an exemption allowed in Title 10 of the *Code of Federal Regulations* (10 CFR) 40.13(a) (but really subject to 10 CFR 40.51(b)(3)). Excavated soils were blended to meet acceptance criteria for the disposal facility.

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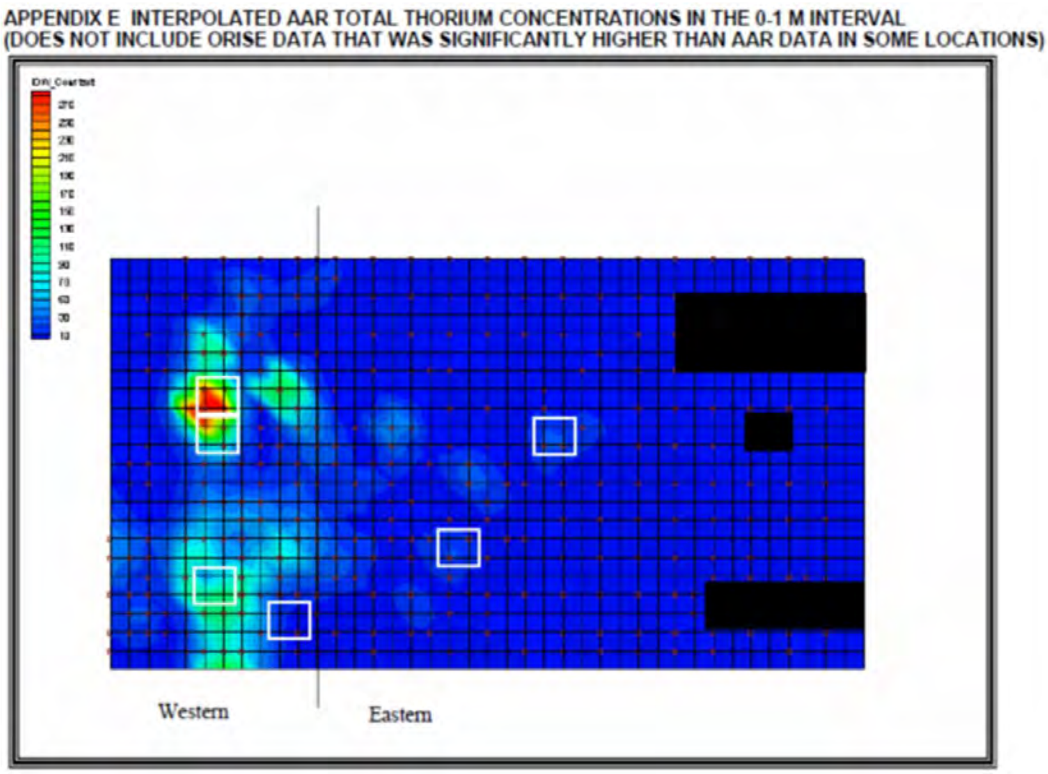

Figure H-1 NRC Use of SADA to Interpolate AAR Survey Data

Source: Barr 2010

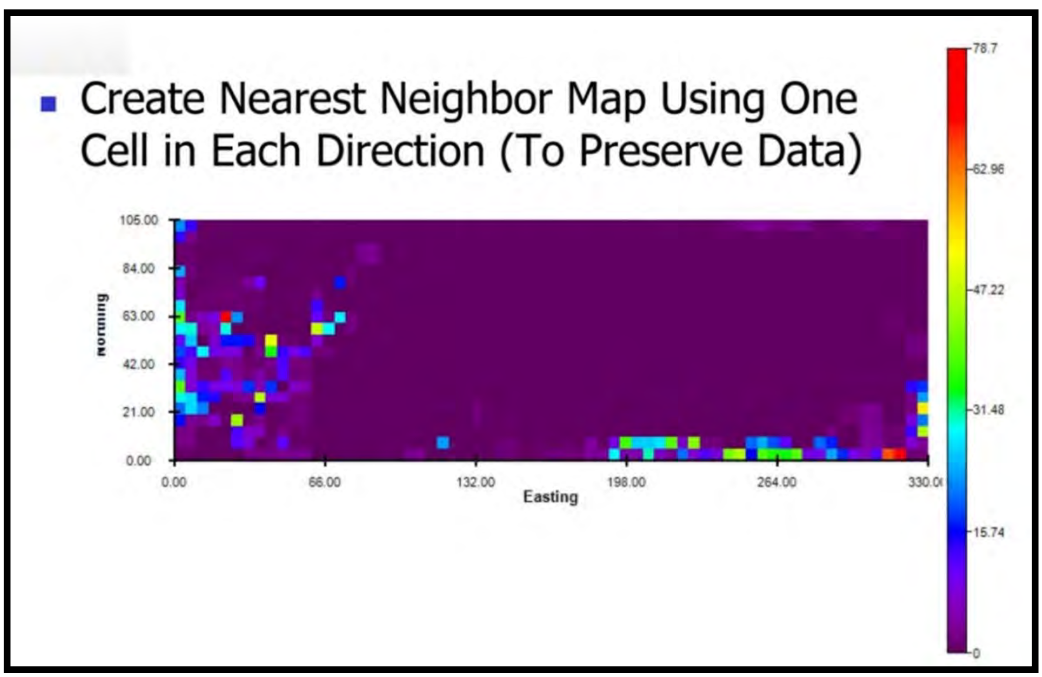

Figure H-2 NRC Use of SADA to Illustrate Nearest Neighbor Map Creation

Source: Barr 2010

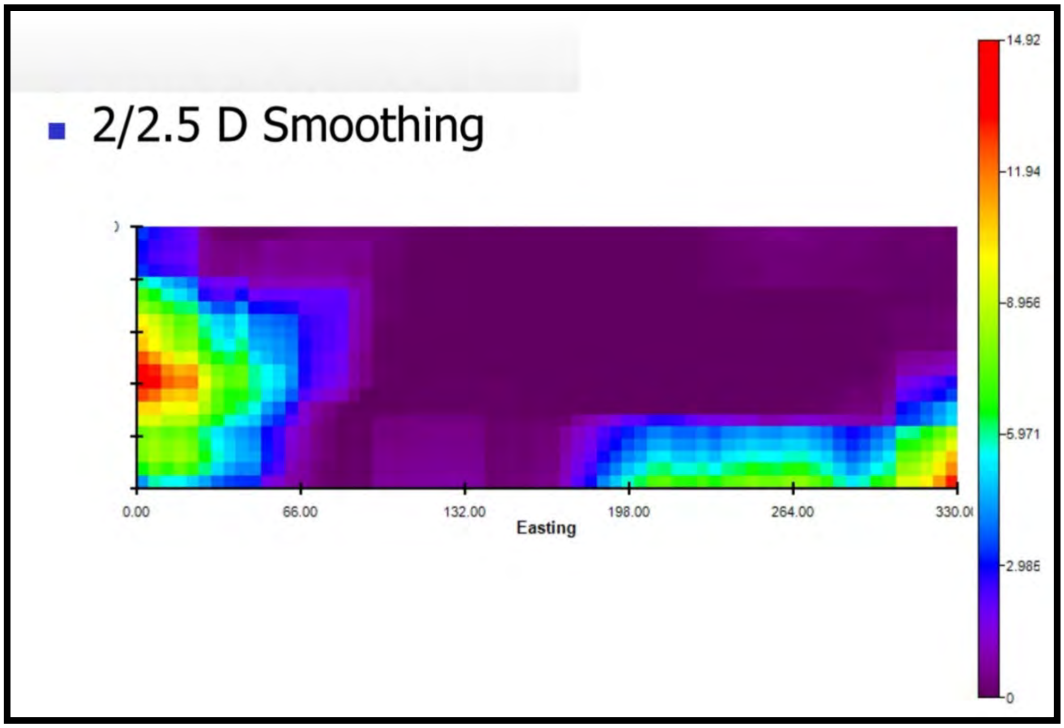

Figure H-3 NRC Use of SADA to Illustrate Smoothing Module

Source: Barr 2010

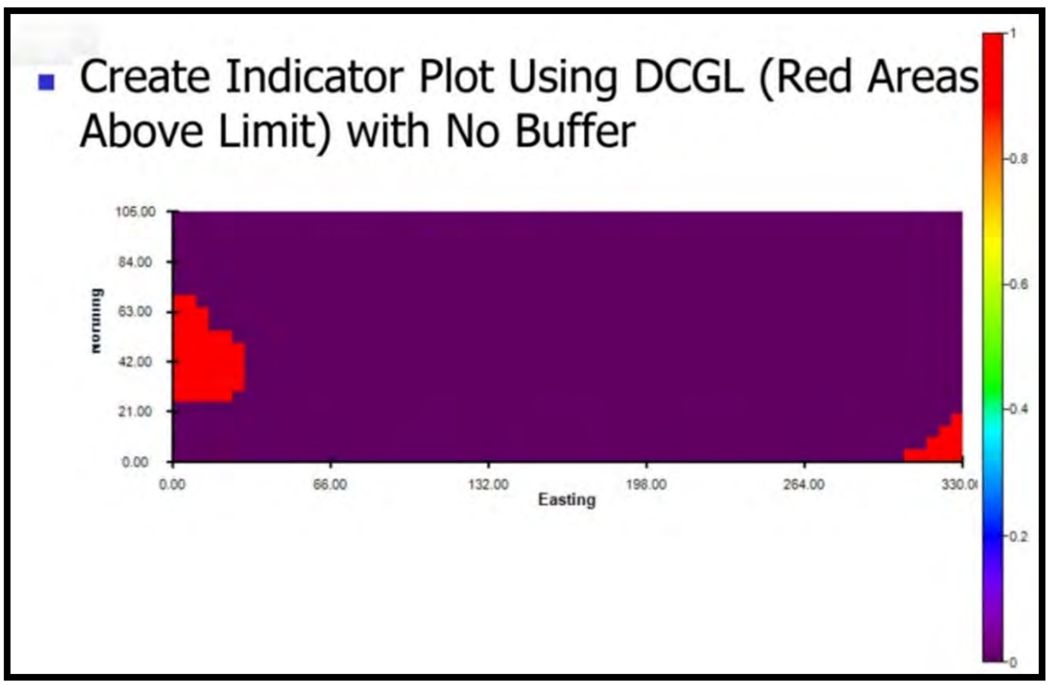

Figure H-4 NRC Use of SADA to Illustrate an Indicator Plot

Source: Barr 2010

H.2 West Valley Demonstration Project

West Valley, NY
Docket No. 0500201

Site of spent fuel reprocessing, contaminated surface and subsurface soils, groundwater, treatment lagoons, disposal facilities. Erosion is a major concern at the site.

Multiple Sets of DCGLs: Surface (0–1 m), subsurface (locate 10 m below grade). Surface DCGLs apply to bottoms and lower side of excavations.

Scenarios/Initiating Events: Resident Farmer
Resident Gardener
Recreationalist
Intrusion (Large Cistern)
Offsite Receptors (Ground Water Erosion).

See Figure H-5 for depiction of erosion scenarios.

Codes Used: RESRAD (surface soil DCGLs including intrusion scenarios that brought material to the surface)
STOMP (ground water transport) and 3D
WEPP (erosion)
CHILD (erosion)
Analytical (erosion)

Excavation or Soil Removal: Planned excavation down to top of lavery till (around 10–15 m below grade) into the water table. Hydraulic barriers to be used for ground water control (see Figure H-6).

Reused Soils: Backfilling with clean soils.

Dose Modeling and Survey Notes: Radionuclides associated with spent fuel reprocessing including strontium (Sr)-90, cesium (Cs)-137, Tc-99, and transuranic radionuclides. The U.S. Department of Energy (DOE) will survey the soils at the bottom of the excavation (top of lavery till) to verify the thickness and concentration of residual radioactivity to ensure consistency with dose modeling assumptions used to derive DCGLs. For example, the DOE assumes that the residual radioactivity is diluted by a factor of 10 with overlying clean soil for the intrusion scenario (drilling of cistern); therefore, the thickness can be only one-tenth of the thickness of the overlying clean material. In the end, ground water pathways were also considered for subsurface residual radioactivity (diffusion of residual radioactivity from the less permeable lavery till upwards into the overlying sand and gravel, water table aquifer) and found to be most limiting in most cases. See Figure H-7 below.

Exposure scenarios for offsite receptors were also considered but not found to be limiting (e.g., erosion of residual radioactivity to site streams and surface water transport to the offsite receptor—Seneca Nation of Indians).

Surface, subsurface (bottom of excavation), and sediment DCGLs were developed. The DOE fractionated the dose limit and allowed 2.5 millirem (mrem) per year (yr) for sediment and 22.5 mrem/yr for surface soils and subsurface (not assumed to be co-located) to consider the cumulative impact of multiple media.

Approach to Surveying of Excess or Survey of Used Soils: Not applicable; will need to demonstrate that soils used to fill excavation are free of residual radioactivity and cover thickness is 10 times residual radioactivity thickness.

Reference Documents:

U.S. Department of Energy, "Phase 1 Decommissioning Plan for the West Valley Demonstration Project," Revision 2, December 2009.
https://www.wv.doe.gov/WVDP_WWW/Document_Index/WVDP_Phase_1_DP_Rev_2.pdf

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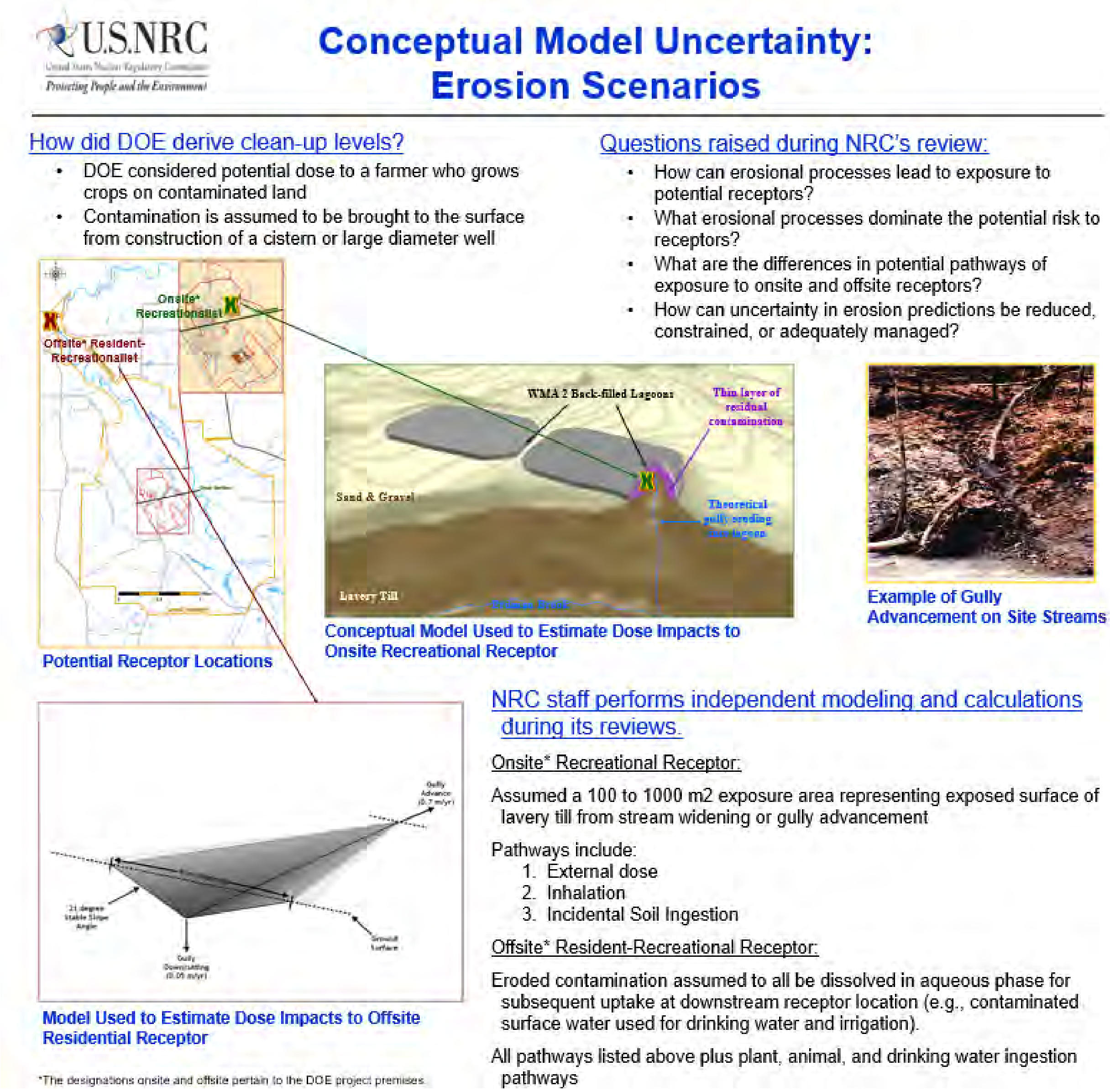


Figure H-5 Depiction of Erosion Scenarios

Source: NRC 2010

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Conceptual Design Of Engineered Hydraulic Barrier Walls

What are Engineered Barriers?

- Constructed containment systems that control movement of groundwater (vertical barriers) or infiltration of surface runoff and rain (caps)

What is the Purpose?

- Facilitate subsurface excavation
- Prevent recontamination of excavation area from contaminated groundwater

What are the Preliminary Designs?

- Two vertical soil-cement-bentonite walls
- Approximately 750 ft long, 2-13 ft wide, and up to 50 ft deep at WMA 1
- Approximately 1,100 ft long, and up to 20 ft deep at WMA 2
- 6.0 E-06 cm/s as maximum permeability
- At least 2 ft into the Lavery till

What are the Risk Significant Aspects of NRC's Review?

- Recontamination
- Worker safety issues
- Potential adverse impacts on other systems and future cleanup options

How Would the Performance of an Engineered Barrier be Evaluated?

- Hydraulic head monitoring (nested piezometers and monitoring wells)
- Groundwater modeling
- Groundwater quality monitoring

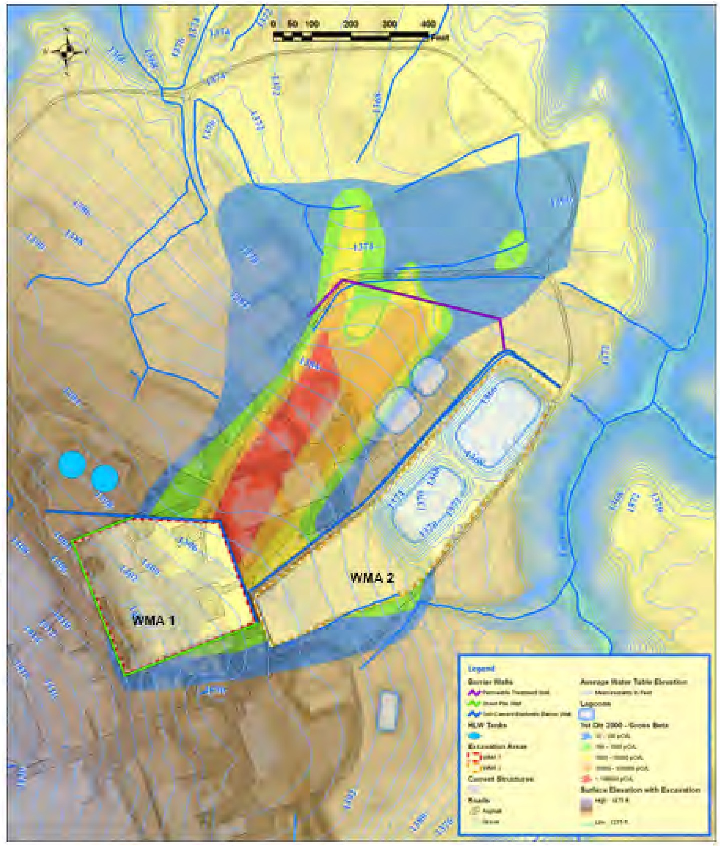


Figure H-6 Depiction of Hydraulic Barriers for Ground Water Control

Source: NRC 2010

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Conceptual Model Uncertainty: Groundwater Dependent Pathways

How did DOE derive clean-up levels?

- DOE considered potential dose to a farmer who grows crops on contaminated land.
- Contamination is assumed to be brought to the surface from construction of a cistern or large diameter well.

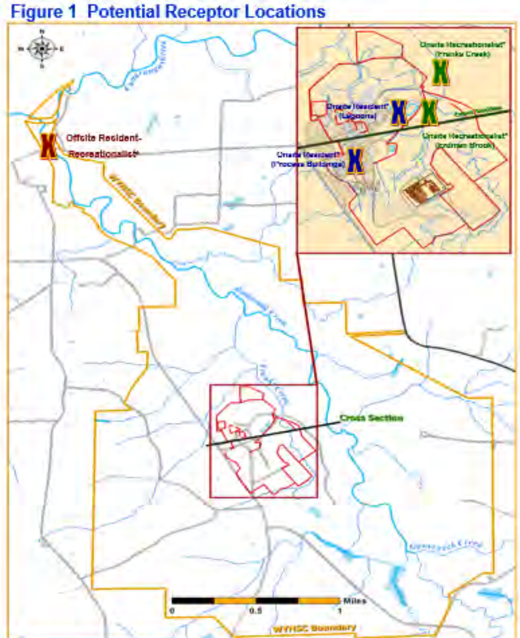
Questions raised during NRC's review:

- What other scenarios could lead to potential exposure to a member of the public?
- How does residual subsurface contamination move through the environment at West Valley?
- How could contamination from multiple sources coalesce in ground and surface water?
- What are the potential pathways of exposure to members of the public at on-site and off-site locations?

NRC staff performs independent modeling and calculations during its reviews:

- Modeling and calculations were conducted to evaluate the potential groundwater pathway risk posed by residual contamination located at the bottom of the excavations.

Figure 1 Potential Receptor Locations



Pathways of Exposure (Potential Receptors)

	External	Inhalation	Soil Ingestion	Plant	Animal	Fish
Onsite* (Resident)	X	X	X	X	X	
Onsite* (Recreationalist)	X	X	X			
Offsite* (Resident & Recreationalist)	X	X	X	X	X	X

*The designations onsite and offsite pertain to the DOE project premises.

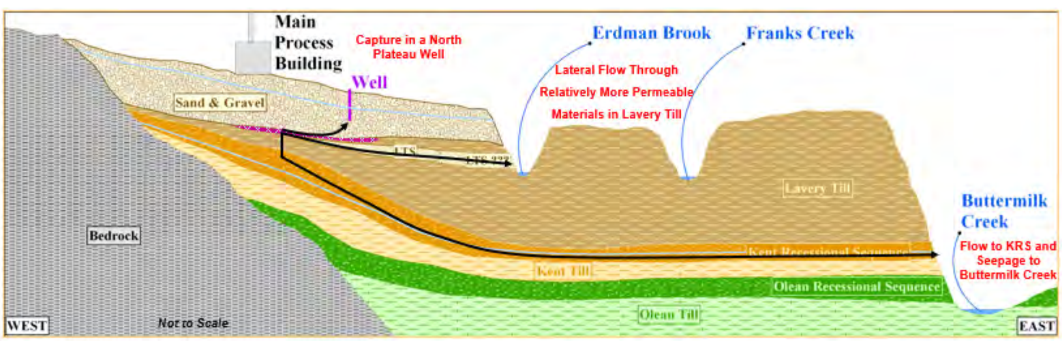


Figure 2 Cross Section Showing Potential Pathways of Exposure Through Ground and Surface Water

Figure H-7 Cross Section Showing Potential Pathways of Exposure Through Ground Surface Water

Source: NRC 2010

H.3 Other Sites

ABB Windsor, Windsor, CT

ABB, Inc., "Decommissioning Plan, Revision 2 (Previously Identified FUSRAP Areas Including Debris Piles & Site Brook), CE Windsor Site, Windsor, Connecticut," Docket 030-03754, August 2010, ADAMS Accession No. ML102310473.

U.S. Nuclear Regulatory Commission, "Technical Evaluation Report—Completion of Decommissioning Activities, ABB, Inc. CE Windsor Site, Windsor, Connecticut," Docket 030-03754, September 2013, ADAMS Accession No. ML13252A297.

Westinghouse Electric Hematite Facility, Festus, MO

U.S. Nuclear Regulatory Commission, "U.S. NRC Safety Evaluation Report on Westinghouse Amendment Request for Approval of Hematite Decommissioning Plan and Associated Supporting Documents," Docket 070-00036, October 2011, ADAMS Accession No. ML112101630.

U.S. Nuclear Regulatory Commission, "Office of Nuclear Material Safety and Safeguards Safety Evaluation Report, Review of Final Status Survey Report for the Hematite Site in Jefferson County, Missouri," Docket 070-00036, September 17, 2018, ADAMS Accession No. ML18241A066.

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[2] This paper discusses intrusion scenarios for buried contamination, volumes of concern and the associated $DCGL_{EMC}$ for these subsurface volumes, optimization of sampling density to meet MARSSIM requirements, and consideration of elevated area concerns. Use with caution as the approach does not consider the ground water pathway, which may drive DCGLs (it considers only intrusion scenarios that bring radioactivity to the surface; also indicates that anything deeper than 0.3 to 0.5 m has zero dose (the root depth in codes such as RESRAD may not be consistent with this assumption)).

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H.4 Lessons Learned and Other Observations

The following sections provide a high-level overview of approaches used by decommissioning sites listed above and are not meant to be exhaustive (i.e., general statements are made about approaches used by licensees to demonstrate compliance with release criteria). Although proposed approaches are listed in some cases, the NRC staff may still be reviewing the acceptability of the proposed approach, and the description of the approach should not be taken as NRC acceptance of the approach. An effort was also made to describe lessons learned when appropriate.

Establishment of DCGLs

Sites established either a unified DCGL or multiple sets of DCGLs:

- Some licensees established both surface (0–15 cm) and subsurface DCGLs below 15 cm to various depths, while others established only one set of DCGLs (e.g., 0–1 m).
- In at least one case, three sets of DCGLs were originally developed for the surface (0–15 cm), root zone (0.15–1.5 m) and subsurface (1.5–6.7 m), and a sum of fractions (SOF) was used to determine the total dose for the entire column. However, in most cases, only a single DCGL for the entire thickness of residual radioactivity from 0–6.7 m (named the uniform DCGL) was used if the release criteria could be met, to avoid complications in tracking residual radioactivity in discrete layers.

Scenarios/Initiating Events and Pathways

Scenarios included resident farmer, resident gardener, and industrial worker.

Pathways considered included the following:

- Industrial worker—direct exposure to external radiation (while indoors and outdoors); inhalation dose from airborne radioactivity; soil ingestion; direct exposure; inhalation dose and ingestion dose from drilling spoils that are brought to the surface during installation of the onsite water supply well into the fill and concrete of backfilled structures; and direct exposure, inhalation dose, and ingestion dose from concrete that is brought to the surface by excavation after license termination

- Resident farmer/gardener—direct exposure to external radiation, inhalation dose from airborne radioactivity, direct ingestion of soil, ingestion of food from crops grown in contaminated soil and irrigated with site water, ingestion of meat and milk from livestock drinking well water and consuming fodder irrigated with well water, ingestion of aquatic food from a nearby pond, ingestion of drinking water (including from an onsite well), and inadvertent ingestion of contaminated dust

- Resident farmer intrusion event—direct exposure, inhalation dose, and ingestion dose from contaminated drilling spoils brought to the surface during installation of an onsite well into the contaminated subsurface material (see pathways listed under resident farmer/gardener above for additional detail)

Codes Used

Example codes used included the following:

- RESRAD
- Visual Sample Plan (VSP)
- DUST-MS
- Analytical (Excel spreadsheet)

Excavation or Soil Removal

Excavation and soil removal approaches included the following:

- Burial pits excavated down to bedrock (6.7 m deep).

- Areas where the DCGL was exceeded were excavated using conventional construction equipment.

- Some licensees evaluated only the excavated bottom soil surface area, while others also surveyed the sidewalls. This practice does not follow draft guidance in NUREG-1757, Volume 2, Revision 2, Appendix G, and can cause difficulty in demonstrating compliance with the release criteria. As stated in Appendix G, although the sidewalls can have a less restrictive survey unit classification (Class 2 or 3) compared to the excavation bottom (Class 1), the side walls are expected to be surveyed.

- Some licensees removed large areas of contaminated surface soil and performed some level of remedial action surveys on the bottom of the excavation but not to the rigor of a FSS before backfilling with clean soil. Then an FSS was performed on the backfilled excavation. This practice does not follow guidance in draft NUREG-1757, Volume 2, Revision 2, Appendix G, and can present difficulty in demonstrating compliance with the release criteria.

Reused Soils

Soil and debris removed during excavation was handled as follows:

- Removed soil and debris were set aside for characterization and containerization.

- “Clean” excavated soil from stockpiles was reused on the site as backfill. Backfilled soils assumed to be “clean” were surveyed before reuse to confirm they were free of residual radioactivity.

- Overburden soils excavated to expose buried components in order to remove the buried pipe or conduit were only temporarily removed, and then the overburden soils were placed back into the same excavation. Surveys of the soil were performed as it was removed.

Dose Modeling and Survey Notes

Dose modeling and surveying approaches included the following:

- For excavations involving industrial and hot waste lines at one site, soil was monitored using a sodium-iodide (NaI) detector (2 inch x 2 inch or 1 inch x 3 inch) during the excavation of the soil from ground level to the top of the piping. If elevated activity is detected at count rates that exceed a value indicating 50 percent or greater of the designated DCGL, then a soil sample was collected and analyzed with the onsite gamma spectroscopy system.

- One licensee surveyed the excavated bottom surface area by taking 55 samples. Each of the statistical sample locations was selected based on a random start, systematic grid placement using the VSP software program. This was combined with a 100-percent scan of the accessible survey areas with a gamma-sensitive NaI detector system.

- Another licensee used multiple survey approaches. Reuse of soil proved to be very complicated, and surveys were not always effective (fuel pellets and recontamination from flooding events were discovered during confirmatory surveys). In general, the licensee used gamma scans during excavation to identify whether soil was a candidate for reuse, scanning soil before it was loaded on a dump truck in lifts, putting the dump truck through a box counter, taking a composite sample from the truck once it was dumped, and analyzing the composite sample using gamma spectroscopy and isotopic analysis for technetium (Tc)-99 and inferring U-234 based on an assumed enrichment ratio. The licensee also put much of the soil through an ISO-Pacific Nuclear Assay Systems S3 soil sorting system as a corrective action to “misses” when performing 12-inch lifts and traditional survey methods. The soil that was not put through the S3 System was spread out to a 6-inch depth and rescanned after its transport to a laydown area (essentially doing an FSS on the soil in 6-inch lifts as it was placed back down). Because there was significant safety margin, the licensee also agreed that any soil from a stockpile placed in a survey unit would have the average SOF of the stockpile added to that SOF otherwise derived for the survey unit, even if soil from more than one stockpile was used in a survey unit, adding conservatism to the compliance demonstration. The DCGLs used for reuse soil SOF determination were uniform DCGLs as opposed to layered DCGLs to facilitate backfill operations (e.g., resolved issues associated with closely monitoring depth of placement of reused soil and potential settling and mixing of reused soils with other layers). The NRC staff notes that these methods provided a significant database of the radionuclides of concern throughout the depth of reused soil that was collected/distributed and gave a high confidence that the release criteria were met.

- One licensee performed a gamma walkover survey over the exposed excavated surface, typically using a 2-inch by 2-inch NaI gamma scintillation detector. Appropriate scanning speed and scanning distance were implemented to ensure that a minimum detectable concentrations (MDC) of 50 percent of the OpDCGL for soil was achieved. Locations with an elevated count rate were identified for additional scanning and/or the collection of biased soil samples to determine whether the elevated count rate indicates the presence of soil concentration in excess of the OpDCGLs. The information obtained during the remedial action and remedial action support surveys (scan results and the analytical data from any associated soil samples) was used to determine whether the remaining exposed soils contain the following:

  – radioactivity concentrations above the applicable OpDCGLs and so require further excavation

  – radioactivity concentrations that are less than the OpDCGLs but require removal to access additional soil or debris that potentially contains radioactivity concentrations above the applicable DCGL

  – radioactivity concentrations that are less than the OpDCGLs and do not require removal

- At one site, if pilings were identified in areas of contaminated soil and the pilings were also found to be contaminated, the contamination would be evaluated volumetrically considering the entire mass of the concrete piling. The resulting volumetrically contaminated volume would be assessed against the soil DCGL in the same manner as the surrounding soil.

- A licensee technical support document examined the response and scan MDC of the Ludlum Model 44-10 NaI detectors for cobalt-60 and Cs-137 radionuclides when the detectors are used for scanning surface soils. If the survey instrument scan MDC was less than the OpDCGLs, then scanning was the primary method for guiding the remediation. Once the scan surveys and the laboratory data obtained from any biased soil samples that may have been collected indicated residual concentrations less than the OpDCGLs, the area was considered suitable for FSS. If the scan MDC was greater than the OpDCGLs, the gamma walkover survey would still be used to initially guide remediation; however, as the levels were reduced to the range of the OpDCGLs, an additional number of biased soil samples were taken to ensure that the area could be released as suitable for an FSS.

- Three-dimensional modeling of characterization data was used at one site to define the gross outline of areas exceeding the soil DCGL. Two exposure scenarios were used for evaluating these elevated areas. In the first scenario, the industrial worker was assumed to work on site 50 weeks per year and the residual radioactivity was covered with a layer of noncontaminated cover (e.g., soil or asphalt) equivalent to the depth below site grade of the residual radioactivity in that elevated area. The second scenario represented a plausible intrusion into the industrial site (construction of a house with a basement is unrealistic at the site). The anticipated intrusion was associated with pipeline installation or foundation construction. As part of the direct dose assessment, the more conservative of the two industrial intrusion activities was evaluated for dose to the intruder. The licensee demonstrated compliance by performing a direct dose assessment of residual radioactivity.

- One site used 50-m^2 core hole spacing (half the recommended 100-m^2 guideline in Section 5.3.3.2 of NUREG-1575, Revision 1, “Multi Agency Radiation Survey and Site Investigation Manual (MARSSIM).” The SOF for each individual sample was compared against surface soil DCGLs. The site applied criteria related to the volume of material that could be above a certain concentration (elevated area type of criteria).

- At one site, surface soil was collected using a split spoon sampling system or by using hand trowels, bucket augers, or other suitable sampling tools, while subsurface soil was sampled by direct push sampling systems (e.g., Geoprobe®) or by the excavation of test pits. Characterization surveys of several inaccessible or not readily accessible subsurface soils were deferred until access was safe. Remedial action surveys were performed in currently inaccessible soil areas that were exposed after removal of asphalt or concrete roadways and parking lots, rail lines, or building foundation pads (slab-on-grade). Radiological assessments of soil areas relied principally on direct and scan radiation measurements using gamma sensitive instrumentation, and samples were also collected from potentially impacted soil, sediment, and surface residues for laboratory analysis.

- Strategies for sampling subsurface soils below basement structures included soil borings or Geoprobe® sampling that was biased to locations having a high potential for the accumulation and migration of radioactive contamination. Any detection of residual radioactivity in subsurface soils adjacent to or under a basement surface resulted in an investigation to assess the potential contamination of the exterior of the structure.

<u>Approach to Surveying of Excess or Used Soils</u>

Approaches to surveying excess or used soils included the following:

- At one site, if soil was excavated to expose buried components, the overburden soil was removed, the component removed or installed, and the overburden soil placed back into the excavation. In these cases, a remedial assessment was performed.

- At one site, the footprint of the excavation was scanned before the excavation was filled. In addition, periodic scans of the soil were performed as it was excavated, and the exposed surfaces of the excavated soil was scanned after it was piled next to the excavation for reuse. A soil sample was taken at any scan location that indicated activity in excess of 50 percent of the soil OpDCGL. Any soil confirmed as containing residual radioactivity at concentrations exceeding 50 percent of the soil OpDCGL was not used to backfill the excavation and was disposed of as waste.

- At one site, for any soil excavation created to remove a potentially contaminated subgrade basement structure, the excavation was subject to an FSS before clean offsite soil was emplaced.

- A radiological assessment was performed before introducing offsite material to one site for use as backfill in a basement, or for any other use from a barrow pit, landfill, or other location. The radiological assessment consisted of a gamma scan and material sampling. Gamma scans were performed in situ, or by package (using a hand-held instrument or through a truck monitor). Material samples were analyzed by gamma spectroscopy.

- One licensee used conventional construction equipment to excavate areas where the DCGL was exceeded. Radiation measurements were used to guide remedial excavation. Excavated soils were loaded into trucks or containers at the site of remediation and moved to the material handling area or shipped in accordance with NRC-authorized transfer to a State-regulated disposal facility. An FSS was performed in each remediated area. Excavated soil that was demonstrated to contain radioactivity concentration lower than the DCGL was returned into an excavation pit. The licensee then backfilled, compacted, graded, and resurfaced remediated areas.

- At one site, overburden soils were removed, the component underneath removed or installed, and the overburden soil placed back into the excavation and a remedial action survey performed. The footprint of the excavation, and areas adjacent to the excavation where the soil was staged, was scanned before the excavation. In addition, periodic scans were performed on the soil as it was excavated, and the exposed surfaces of the excavated soil were scanned after the soil was piled next to the excavation for reuse. A soil sample was acquired at any scan location that indicated activity in excess of 50 percent of the soil OpDCGL. Any soil confirmed to contain residual radioactivity at concentrations exceeding 50 percent of the soil OpDCGL was not used to backfill the excavation and was disposed of as waste.

Other Observations and Findings

Other observations and findings include the following:

- One site also considered hard to detect radionuclides and established surrogate relationships.

- Partial fuel pellet(s) were discovered during a confirmatory survey, which called into question the adequacy and methodology of scans. The licensee revised the scanning methods for the radionuclides of concern. It continued to use the 2-inch x 2-inch NaI detector and plotting of data, but it also used a slower speed and closer scanning distance and credited the postprocessing of the data (i.e., open land scans at a rate of 1 foot per second and a 2-inch average distance from the surface, in contrast to the general guidance in MARSSIM, for 0.5 m per second and 6-inch average distance). In addition, the licensee's postprocessing of the data, performed to identify count elevations to be further investigated based on exceeding the average plus 3 times the standard deviation, resulted in using a surveyor efficiency of 0.75 (versus a surveyor efficiency of 0.5 in MARSSIM). These modified methods were able to achieve acceptably low scan MDCs. Similar to previous efforts, the technician performing the scan had instructions to investigate further if the count rates were notably differentiated based on the audible signals or if the count rate exceeded the action level set at the values in the decommissioning plan. The licensee also modified its excavation methods to excavate in 6-inch lifts instead of 12-inch lifts to maximize the sensitivity of scanning during the excavation process.

- NRC inspectors raised concerns about scanning and sampling of excavation sidewalls at one site, noting that the licensee was not meeting its commitment to perform a 100-percent scan of the exposed and accessible surfaces in the Class 1 land survey units. The licensee indicated that it was not scanning the sidewalls of the excavation because of safety concerns and improper equipment. Instead, the licensee performed discretionary sidewall sampling for Tc-99 if the sidewall areas of an excavation exceeded 5 percent of the total area of the survey unit and to evaluate any inaccessible surfaces by review of the scanning plot to determine whether count rates were trending up towards the inaccessible surface. However, some areas were backfilled before sidewall scanning or sampling could be performed. No foreign materials (e.g., discolored soil areas or nonsoil materials) were apparent in these areas before backfilling excavations, and the sampling and scanning data obtained indicated that an exceedance of the DCGLw criteria was unlikely in the limited areas where scanning of excavation sidewalls did not occur. The staff therefore found the licensee's sidewall scanning and sampling methods adequate to demonstrate satisfaction of the FSS commitments even though it did not scan some difficult-to-access areas of some excavations.

- Excavations of significant depth that are backfilled but only surveyed on the surface create uncertainty of the contaminant levels for the entirety of the backfilled materials that is hard to resolve. It is preferrable to have characterization data that are representative of the entire depth and area of the backfilled materials. This can be from data collected during stockpile generation or as the material is placed into an excavation. The data should address all radionuclides of concern in a manner consistent with FSSs as opposed to only scanning/screening of the materials. The NRC staff currently prefers to see stockpile data generated as the material is exposed and being moved to the stockpile (e.g., in 6-inch lifts). A licensee should use the data quality objectives process to establish a method that provides reasonable confidence of the average quantity of residual radioactivity in reuse soil while also allowing the screening of soil that exceeds the DCGL values so that it can be segregated and disposed as waste.

APPENDIX I

CONVEYORIZED SURVEY MONITOR

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Table

I.1 Conveyorized Survey Monitors

NUREG-1761, “Radiological Surveys for Controlling Release of Solid Materials,” issued July 2002 (NRC 2002), provides general insight into the characteristics, design, and application of conveyorized survey monitors (CSMs). They offer a form of automation that may be particularly well suited for use where significant quantities of bulk material are subject to clearance requirements. As the name implies, these systems operate by moving materials past radiation detectors using a conveyor system, while automatically storing and analyzing the resulting signals. The radiation detectors themselves can be of any type and are chosen to match the application. The most common detectors in use are sodium iodide (NaI) crystals for gamma detection and thin-window proportional counters for beta detection (NRC 2002).

The material in this subsection should be considered a direct quote (NRC 2002) except for paragraph sequencing:

> Conveyorized survey monitors typically include a motorized conveyor, a detector array, supporting measurement electronics, and an automated data acquisition subsystem. Monitors may also include segmented pathways along the conveyor so that suspect material may be transported to a destination other than that of the non-suspect (or releasable) material.
>
> The conveyor portion of a system consists of a belt that is moved by a variable-speed motor from a loading area, past a detector assembly or set of assemblies, and onto the final destination, which may be either a disposal container or an intermediate pile. If a mechanical diverter is used, the system controls the final material destination based upon user-configured measurement parameters. Without automated segmentation of the material, a system would need to be used in a “shutdown” mode to allow manual separation of suspect material.
>
> Since the conveyor operates in a continuous loop, it creates the possibility for cross-contamination on the belt. When processing materials with a low probability of contamination, as is usually the case during clearance surveys, this issue is of little concern.
>
> ***Automated Data Processing (ADP)***—Measurements collected using a CSM are usually digitized before being analyzed. The data are analyzed on-the-fly using a preset algorithm, and decisions concerning suspect materials are usually made in real-time. The resulting data, together with the analysis results, are then archived to a long-term digital storage medium.
>
> The counting parameters associated with measuring a stream of material passing near a CSM detector are very similar to those encountered with other detection systems. Although each manufacturer’s system employs a proprietary analysis mechanism, the fundamental physics and statistical parameters are independent of the software design. As such, one can estimate the detection sensitivity of a CSM detector system without detailed knowledge of the analysis methods that are actually used, provided that the type of detector and electronic configuration are known.
>
> A very interesting capability that is unique to automated systems is the ability to perform multiple, parallel analyses. As a practical example, a CSM could be configured to monitor over multiple time intervals, in order to optimize the

detection capability for both small and large regions at the same time. Additionally, the data collected from shorter time intervals could be used to augment the decision criterion applied to longer time intervals, so that small increases over the long interval may be corrected for anomalies (e.g., such as from potential hot spots) observed during short-interval measurements.

Detectors—The heart of any radiation measurement system is the detector(s). The selection and configuration of detectors and associated electronics is the single most important aspect of designing any radiation measurement device, since it defines the system's baseline capability. Auxiliary components, such as data analysis engines and hardware controls, certainly affect the overall performance of a CSM, but not to the same degree as the detector(s). The ability of any detector to measure radiation is defined by physical constraints that cannot be easily manipulated or changed by users, so the initial selection of this component more-or-less establishes the system's capability.

Gross screening of gamma-emitting radionuclides is usually best performed using scintillation detectors, such as NaI or plastic scintillators. While these detectors are not the best selection for quantitative measurement of complex spectra, their excellent detection efficiencies and relatively low cost make them top candidates for gross gamma measurement applications where CSMs may be desired. Solid-state gamma-ray detectors, such as high-purity germanium (HPGe) detectors, offer much better assay capability, but are fairly expensive to purchase and maintain, especially if one is interested in achieving the same level of detection efficiency offered by large-volume scintillation crystals.

The type, shape, encapsulation, and electronic configuration of a scintillation detector determine its overall detection efficiency and background response, thereby defining its signal-to-noise ratio. Consequently, it is important to select detectors that balance background response with detection efficiency for the suspected radionuclide(s). As an example, a 3" x 3" NaI detector yields a good signal-to-background ratio for a high-energy gamma-emitter such as Co-60, but it is a poor selection for a low-energy emitter such as Am-241. Beyond the base selection of the detector material and physical design, one should consider the selection and placement of photodetectors and driving electronics when considering the optimization of a system. For example, simply reducing (or increasing) the detection input threshold at the amplifier stage can sometimes critically alter the overall system performance.

High-purity germanium detectors could play an important role in some CSM systems, even though they are more expensive and difficult to maintain. These detectors are excellent for gamma-ray spectrometry, as they facilitate an unparalleled capability for nondestructive identification and quantification of gamma-emitting radionuclides. With the exception of very expensive large-volume crystals, however, these detectors cannot compete with low-cost scintillation materials when gross sensitivity is desired. Their use in a CSM system could be warranted in some instances for nuclide identification following a positive detection during a gross scan. For example, a system could plausibly be configured to automatically stop a conveyor following a positive *detect,* and then attempt to identify the gamma-emitting radionuclides present before passing the material to its final destination.

Measurement of beta-emitting radionuclides in (or on) bulk materials may also be possible, depending on the radionuclide, material type, and release limit. Beta detection can be accomplished using thin-window gas-filled detectors, such as gas proportional and Geiger-Mueller detectors, and thin-windowed scintillators. The most likely candidate for measuring beta-emitters is large-area gas flow through proportional detectors with thin Mylar entrance windows; however, large-area sealed proportional and GM detectors are also expected to perform well. Scintillation materials universally suffer from an inferior signal-to-background ratio when measuring beta-emitters, but they may still be adequate for some applications.

The surface area and window thickness of beta detectors are the critical design parameters that affect detection efficiency. Ideally, one would desire a large array of small detectors, so that each segment monitors a small area while keeping its background to a low level. This would be an expensive option, so actual systems usually employ intermediate-sized detectors with thin windows, with each detector often occupying 100 cm^2 to 500 cm^2 of sensitive area. Smaller detectors are also often grouped together in parallel assemblies with common electronics to minimize the overall system cost. These detector sizes provide a good balance between cost and detection sensitivity for CSM applications. As another, somewhat uncommon option for CSM systems, electronically segmented proportional counters overcome the size-versus-background design issue. Detector systems operating in this mode attempt to subdivide large-area proportional detectors into small, virtual regions by using advanced timing electronics to optimize the signal-to-background ratio for small areas, while keeping the number of detectors low. These designs require more advanced electronics and analysis algorithms and are not typically used in CSM systems today.

I.2 Detection Sensitivity[1]

The selection of detectors and supporting electronics is the key to optimizing overall system performance for specific applications. Other parameters that should be considered include the quantity and placement of detectors, as well as the speed of materials past the sensitive regions of the detector(s).

As a rule, the signal-to-background ratio of a radiation detector array is directly proportional to the square root of the number of detectors employed when measuring uniform radiation fields. To illustrate this principle, two identical detectors operated in tandem (parallel) yield a signal-to-background ratio that is about 40 percent higher than the ratio that a single detector would yield when measuring a material with homogeneously distributed contamination. Grouping the detectors together in parallel, with a single set of driving electronics, reduces the detection ability for small regions near a given detector. By contrast, if the two detectors are operated independently of each other, with separate driving electronics, the measurement

[1] NUREG-1507, Revision 1, “Minimum Detectable Concentrations with Typical Radiation Survey for Instruments for Various Contaminants and Field Conditions,” issued August 2020 (NRC 2020), introduces some concepts related to GPS/GIS-based techniques and methodologies along with considerations for detection efficiency calculations, background interferences, signal degradation, and other topics associated with radiation survey instrumentation. The primary reference for this section, NUREG-1761, has not been updated, but no significant changes are anticipated.

sensitivity for homogeneous media would also be 40 percent higher than the capability of a single detector, but without penalizing the ability to detect small, elevated regions.

Placement is also critical—particularly for the measurement of beta-emitters—since the inverse square relationship and absorption within the intermediate air can greatly affect sensitivity. While this is less important for gamma-detection equipment, it is essential to place beta measurement detectors as close as practical to the material being monitored. As with portable survey equipment, it is also advisable to establish a CSM detector configuration that offers acceptable detection ability without placing the detector in harm's way (as might occur when jagged materials pass too near a fragile detector face).

Belt speed significantly affects the measurement capability of a CSM. Detection sensitivity for small- to intermediate-sized regions varies (roughly) with the square root of the observation interval (time) for any segment of material being monitored. In other words, a slower moving belt facilitates a more sensitive detection capability for smaller regions. Interestingly, belt speed has no impact on detection ability for a continuous stream of truly homogeneous materials since, by definition, the radioactivity is present at an equal concentration throughout all the material. In practice, however, material with homogeneously distributed contamination is atypical, and the detection ability for smaller regions should be considered when designing a scan protocol.

To deal with this fact while using a CSM during clearance surveys, one can assume, for better or worse, that homogeneity exists within subregions of the suspect material and, to be consistent with traditional survey design, these regions should be labeled as survey units or batches. The desired belt speed should, therefore, be determined as a function of the release limit (derived concentration guideline level), the allocated survey unit size, and the detection efficiency of the system for the target media and expected radionuclide(s).

Detection Efficiency for Gamma-Emitters Using NaI Detectors—The detection ability of sodium iodide (NaI) detectors operating in a gross count rate mode[2] will depend on the design, quantity, and electronic configuration of selected detectors. For purposes of providing an example of an expected detection capability, this section discusses a hypothetical system that has been configured with moderately sized 3-inch x 3-inch cylindrical crystals with supporting electronics. It is assumed that three such detectors will be operated in tandem in a detector *bank* and that the total detector volume per bank will therefore be about 1,000 cubic centimeters (cm^3).

A common radionuclide that may be measured using such a system would be cesium (Cs)-137—with a primary gamma ray emitted by its daughter (barium (Ba)-137m) at 662 kiloelectronvolts (keV) with an emission ratio of 0.85. If one assumes that cesium is mixed relatively homogeneously within each region of a CSM conveyor stream, then a fairly accurate estimate of detection ability can be calculated by coupling empirical data with modeled exposure rates. The two empirical parameters that should be known are the total background count rate and the detection efficiency for Cs-137. In general, although certainly depending on location and configuration, the background count rate for 3-inch x 3-inch cylindrical NaI crystals operating in full-open gross count rate mode will be in the range of about 8×10^3 to 1×10^4 counts per minute (cpm), and the detection efficiency will be approximately 4×10^6 cpm per milliroentgen per hour (mR/h) when measuring Cs-137. For three detectors ganged into a single electronic

[2] *Gross count rate mode* refers to operating a detector such that all measured pulses within a pulse-height window, whether it be narrow or wide open, are summed together into a single value representing the gross count rate for the detector configuration being used.

bank, these values correlate to a total system background of about $2.7x10^4$ cpm and a total detection efficiency of about $1.2x10^7$ cpm per mR/h.

These parameters can be coupled to calculated exposure rates in the vicinity of material passing along a conveyor system to evaluate detection sensitivity as a function of the material geometry and radionuclide. As an example application, consider a scenario in which a CSM will be used to scan for Cs-137 in soil having a bulk density of 2 grams per cubic centimeter (g/cm^3). The centerline of the three detectors is assumed to be placed approximately 15 cm above a 76-cm (30-inch) wide conveyor belt such that they are evenly spaced across the breadth of the belt at 13, 38, and 64 cm (5, 15, and 25 inches) from one edge. If the soil is assumed to be 2.5-cm (1-inch) thick and to extend on the conveyor for 76 cm (30 inches) along the conveyor to either side of the detector bank, then the expected exposure rate will be about 120 mR/h per microcurie per gram (µCi/g) at the two outside detectors and approximately 140 mR/h per µCi/g for the center detector. Coupling these data with the expected detection efficiency previously given, the total efficiency for this geometry—using all three detectors in an electronically ganged configuration—is expected to be about $1.5x10^3$ cpm per picocurie/gram (pCi/g) of Cs-137. If the soil thickness is increased to 10 cm (4 inches) and the detectors are positioned 20 cm (8 inches) from the belt, then the system detection efficiency will increase to about $4x10^3$ cpm per pCi/g of Cs-137. The latter case represents a count rate increase of 15 percent above background for each pCi/g of Cs-137.

The MDC can be estimated while operating such a detector configuration in a scan mode by assuming a false-positive detection rate of 1 percent and a false-negative detection rate of 5 percent (Currie 1968). These values mean that true contamination will be missed 5 percent of the time, and false alarms will occur 1 percent of the time. For an observation interval of 6 seconds, the MDC for a 2.5-cm (1-inch) thick layer of soil containing Cs-137 is expected to be about 2 pCi/g and will decrease to 0.7 pCi/g when the soil thickness is increased to 10 cm (4 inches).

Detection Efficiency for Beta-Emitters Using Thin-Window Proportional Detectors—Beta particles originating within or on a target media usually undergo significant interaction before reaching the sensitive volume of a CSM detector. As such, the process for estimating detection ability is significantly more problematic than is necessary when evaluating detection capability for gamma-emitting radionuclides. As previously mentioned, the most common type of detector for this application is a thin-window gas-flow proportional detector. Such detectors have a thin Mylar entrance window with a density thickness ranging from less than 1 to a few milligrams per square centimeter (mg/cm^2). Although the mixture may vary, the most commonly used gas is phosphorus (P)-10, containing 90 percent argon and 10 percent methane.

This section provides an analysis of the beta detection ability for gas-flow proportional counters and, in particular, that which is applicable to a CSM. The first scenario considers surface contamination with technetium (Tc)-99 and strontium (Sr)-90 on flat surfaces, while the second looks at Tc-99 and Sr-90 in soil, and the third evaluates Cs-137 in soil. These evaluations are summarized in the following paragraphs.

Surface activity refers to contamination on the surface of solid materials. As simple as this sounds, it is difficult to define what constitutes a "surface," since real-world materials have a thickness when viewed from the perspective of a radioactive atom deposited *within* their surfaces. One might define surface contamination as the activity contained within a surface layer that has a thickness equal to that of the saturation layer (ISO 1988[3]), where the thickness

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[3] Since NUREG-1761 was published, ISO 1988 has been revised by ISO 2016-3 (ISO 2016). ISO 2016-3 discusses the saturation layer thickness and the emergence factor *E.*

of the saturation layer is defined as the thickness of the medium (surface material) equal to the maximum range of the specified particulate radiation. While some materials are more porous than others, all have some level of absorptive capacity. The definition of “surface,” therefore, becomes significant when evaluating the detection ability for charged particles emitted from the surface of materials and is amplified significantly when constructing a model.

Consider an 80-cm (31-inch) wide conveyor using five proportional counters with open, or sensitive, areas of 500-cm^2 each, placed 5 cm (2 inches) above the belt surface. The detectors are rectangular in shape, with each window region measuring 50 cm by 10 cm (20 inches by 4 inches), with the long dimension placed parallel to the direction of belt travel in the CSM. If five such detectors are placed side by side across the breadth of the conveyor, the total sensitive area is 2,500 cm^2 (390 inches^2). Each detector is assumed to be configured individually (not grouped), with 0.8 mg/cm^2 of window material without protective screens, and the detection capability is assumed to have been maximized for low- to intermediate-energy beta detection. The background response for such a detector is in the range of 2 to 3 cpm/cm^2 of window area, so each detector has a nonshielded typical background of about 1,300 cpm. Again, the reader should note that this configuration is defined for the purpose of estimating beta detection ability as an example; however, the detection abilities of actual systems will vary slightly by manufacturer.

First, the pure beta-emitting radionuclides Tc-99 and Sr-90(Y-90), having maximum-energy beta emissions of 294 and 546 keV, respectively, are assumed to be placed onto the surface of a thin, flat plane in contact with a CSM conveyor belt. Although unrealistic for most real-world measurement scenarios, this finite plane, zero-thickness geometry provides the highest possible beta-detection sensitivity for a system without improving the detector-to-belt distance. As an extension to this *pure* geometry, it is then assumed that the radionuclides are not restricted to the outermost surface, but instead that they have absorbed homogeneously within the top 50 micrometers (0.002 inches) of a masonry-type material (e.g., cement) having a bulk density of 2 g/cm^3. This scenario is much more plausible when evaluating real-world applications. Table I-1 presents the results of these geometry calculations.

The second geometry places the same isotopes (i.e., Tc-99 and Sr-90(Y-90)), into a soil matrix and varies the depth of the material from 0.1 to 1 cm (0.04 to 0.4 inches), while keeping the belt-to-detector distance constant. The results of this analysis display, both qualitatively and quantitatively, the impact on detection capability that occurs when beta particles interact within the source-matrix material. Table I-1 presents the results.

Finally, the isotope Cs-137, which is both a beta- and a gamma-emitter, is modeled within a soil matrix. Cs-137 decays with the emission of a 512-keV max beta 94.6 percent of the time, and decays with the emission of a 1,173-keVmax beta for the remainder. As previously mentioned, Ba-137m is produced by 94.6 percent of Cs-137 decays, and it, in turn, emits a 662-keV photon during 90 percent of its decays, yielding an overall γ-emission ratio of 0.85. Although not previously discussed in this section, gas-flow proportional counters also detect ionizing electromagnetic radiations (e.g., gamma and x-rays) by measuring secondary electrons produced both within and outside the gas volume. The probability of interaction varies; however, the sensitivity is roughly proportional to the mass of intervening material within the vicinity of the detector, times the probability of interaction within the mass, times the fraction of those particles carrying enough energy to travel into the detector. For Cs-137, the intrinsic efficiency expected with a thin-window proportional detector is about 0.01 counts per photon. The photon detection capability for this scenario was estimated for each CSM detector by calculating the average solid-angle for the geometry and coupling the result with the activity, source-material absorption probability, and finally, the detector interaction probability. Table I-1 presents the result for the summed beta and gamma detection capability.

Table I-1 Model Results for the Detection Capability of a CSM Configured with a Bank of 500-cm^2 Gas Proportional Detectors

Isotope	Soil[a] Thickness (cm)	Single 500-cm^2 Detector[(b)]		Five Detectors Grouped as One 2,500-cm^3 Detector	
		Efficiency (cpm per pCi/g)	$MDC_{6\text{-sec},95\%}$[(c)] (pCi/g)	Efficiency (cpm per pCi/g)	$MDC_{6\text{-sec},95\%}$ (pCi/g)
Tc-99	0.5	1	650	5	300
	1.0	1	650	5	300
Sr-90	0.5	6	110	30	50
	1.0	6	110	30	50
Y-90	0.5	60	10	300	5
	1.0	60	10	300	5
Cs-137[(d)]	0.5	10	65	50	30
	0.8	12	55	60	25
	1.0	14	45	70	20

Source: NUREG-1761 (NRC 2002)

a Soil describes a homogeneous mixture with a bulk density of 2 g/cm^3.

b Single detector values represent the average response expected for five detectors spread across the breadth of an 80-cm wide CSM. All values have been rounded to no more than two significant digits.

c MDC calculated including the variability of background for each 500-cm^2 detector equal to 130 counts during 6-second count intervals (1,300 cpm), based on a given belt speed. The probability of a false detection is assumed to be set at 1 percent, and the probability of missing existing (true) contamination is assumed at 5 percent. Results have been rounded to no more than two significant digits.

d Detection ability calculated for beta emission from Cs-137 as well as gamma emissions from Ba-137m. The observed increase in detection efficiency with soil thickness is due to the increased number of 662-keV gamma rays produced with increased soil mass.

Conveyor Survey Monitor Scan MDCs—The scan MDC for a CSM can be estimated using Equation I-1, with some modification to account for the automated nature of a CSM. That is, the parameters that impact the CSM scan MDC include the detection limit, efficiency, and sample size. The detection limit is based on the background counts obtained over the counting interval and the acceptable rate of true (correct detection) and false positives. The background level depends on the nature of the material, while the counting interval is a function of both the detector's field-of-view and the system belt speed (i.e., it establishes the length of time that the detector(s) can respond to a fixed length of material).

$$MDC = k\ \frac{detection\ limit}{efficiency \times sample\ size} \qquad \text{(I-1)}$$

where *k* is a unit conversion (from instrument response to activity and the desired units).

The minimum detectable count rate (MDCR) can be calculated for the CSM in much the same manner as for conventional scans, with the primary difference being that automated systems interpret the signal stream (data) using a computer-based analysis algorithm rather than by calculation (Equation I-2):

$$MDCR = d' \sqrt{b_i}\ (60/i) \tag{I-2}$$

where d' = detectability index (the value can be obtained from Table 6.5 in MARSSIM; for a false positive proportion of 0.6 with a true positive proportion of 0.95, this value is 1.38.

b_i = background counts in the observational interval.

i = observational interval (in seconds), based on the scan speed and areal extent of the contamination.

Sample or survey unit size is a function of the belt geometry, speed (which establishes the observation interval), and the detector's field-of view and, therefore, has a fundamental impact on the scanning detection limit (cpm) and MDC (pCi/g) of a CSM. The detection efficiency of a CSM depends on the detector characteristics, nature of the contamination, the material being surveyed, and source-to-detector geometry.

I.3 Survey Design Considerations for the Conveyorized Survey Monitor

Conveyorized survey monitors are expected to be used in conjunction with other survey methods during the release of materials for unrestricted use. These relatively massive devices are primarily designed for scanning applications; however, it is possible to construct control algorithms that combine complementary survey stages. Examples include the combination of different detector types, scan and static measurement modes, and the ability to make parallel decisions based on various combinations of measurement results. Ultimately, it is expected that CSM machines could be applied as an advanced, automated scanning process in lieu of using hand-held equipment.

A number of design decisions can be made for such a CSM system to help automate the clearance of material. A configuration decision might be to use the NaI detectors to look for Cs-137 and to use gas-proportional detectors to monitor gross beta emissions from Y-90 and, to a much lesser degree, Sr-90 and Cs-137.

To reiterate, all of these detection sensitivity values were calculated for 6-second observation intervals, while assuming 5 percent false-negative and 1 percent false-positive detection probabilities. The detection capabilities for the target radionuclides for a 2.5-cm (1-inch) thick layer of material are less than the hypothetical release limits. Therefore, it is plausible that the CSM could be used for most of the release scan process without complicated detection schemes. It is important to recognize that the premise of homogeneously distributed contamination over the volume of the solid material is the basis for assuming that the beta-emitting radionuclides are on or near the material's surface. Otherwise, there is only a slim likelihood of detecting a discrete amount of Sr-90(Y-90) activity a few millimeters beneath the soil surface.

I.4 References

U.S. Nuclear Regulatory Commission (2002). "Radiological Surveys for Controlling Release of Solid Materials, Draft Report for Comment," NUREG-1761, Washington, DC, July 2002.

— — — (2020). "Minimum Detectable Concentrations with Typical Radiation Survey for Instruments for Various Contaminants and Field Conditions," NUREG-1507, Revision 1, Office of Nuclear Material Safety and Safeguards, Washington, DC, August 2020.

International Organization for Standardization (ISO) (1988). ISO 7503-1, "Evaluation of Surface Contamination—Part 1: Beta Emitters and Alpha Emitters," First Edition, Geneva, Switzerland, 1988.

— — — (2016). "Measurement of Radioactivity—Measurement and Valuation of Surface Contamination—Part 3: Apparatus Calibration," ISO 7503-3:2016, Geneva, Switzerland, 2016.

APPENDIX J

COMMERCIALLY AVAILABLE EQUIPMENT

CONSIDERATIONS

- Regulators generally expect some level of quality control to verify and quantify the contaminant concentrations in the resulting segregated soil before its disposal or reuse on site.
- While scanning is good, does it provide sufficient documentation to "prove" the levels of contamination if trying to show that a site meets derived concentration guidelines?
- What if hard-to-detect radionuclides of concern are also present?
- What should be provided in a final status survey if that is the objective?
- A licensee's data quality objective process should address use of soil sorting machines.

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Figures

J.1 ANTECH Series G3107-1000 Soil Measuring and Segregation System

ANTECH Corp.
9050 Marshall Court
Westminster, CO
https://www.antech-inc.com/wpcms/wp-content/uploads/G3107-1000-SMSS-technical-note-pdf.pdf?x23691

The ANTECH Series G3107-1000 Soil Measuring and Segregation System (SMSS) is designed (see Figure J-1) and manufactured by ANTECH for the measurement and segregation of radioactive contaminated soil. The G3107 consists of a soil conveyor system with a sensitive large-volume gamma ray scintillation detector for detecting low levels of radioactive contamination in soil or rubble passing along the conveyor in close proximity to the detector. The variable speed belt conveyor is connected to a three-way soil diverter or sorter, which is controlled by the detector. Radioactive contaminated soil is diverted in one of three ways depending on whether it is below the lower level contamination concentration threshold, above the upper level contamination concentration threshold, or between the thresholds. Two-way diversion in relation to a single contamination concentration threshold is also possible.

The system can also detect "hot spots" or small objects of significantly higher activity. The system can be configured to divert small volumes of soil associated with a hot spot. Alternatively, the measurement conveyor can be stopped at a precise point so that the hot spot material can be located while on the measurement conveyor and manually removed.

Figure J-1 ANTECH Series G3107-1000 SMSS

Source: ANTECH
https://www.antech-inc.com/products/g3107-1000/

J.2 Amec Foster Wheeler—Orion ScanSort^{SM}

Amec Foster Wheeler Environment & Infrastructure, Inc.
2275 Logos Court, Suite A
Grand Junction, CO
https://www.headquarterscontacts.com/amec-foster-wheeler/

Amec Foster Wheeler's proprietary ScanSort technology (see Figure J-2) is a conveyor-based system that accurately assays, measures, and sorts material by segregating scanned material into above-criteria and below-criteria discharge piles using criteria supplied by the client for one or more radioactive isotopes. Custom detectors, proprietary scanning spectroscopy software, a rapid reversing conveyor, and customizable reporting software are unique to the ScanSort^{SM} technology. All-weather scanning and sorting of wet or dry material, including soil, crushed stone and concrete, and slurry, are provided. Depending on the type of material and the detection criteria, the technology can process and segregate up to 200 tons per hour. ORION ScanSort^{SM} claims significant benefits over traditional sorting methods, such as reducing waste volumes by up to 95 percent; scanning excavated materials precisely and accurately; and reduced manpower, transport, and disposal costs.

Figure J-2 ORION ScanSort Technology

Source: https://www.dndkm.org/Technology/TechnologyFactSheet.aspx?TechnologyID=1369

J.3 ISO-PACIFIC S3

ISO-PACIFIC Remediation Technologies, Inc
2920 George Washington Way, Suite 101
Richland, WA
http://isopacific.net/

The ISO-Pacific S3 utilizes a 72-inch-wide sorter belt, which can accommodate a layer up to 6 inches in depth (see Figure J-3). The material is conveyed below the detector array in a thin layer, the depth and density of which is matched to the photon emission and attenuation characteristics of the contaminant of concern. There are no ”guess-timates” of attenuated subgrade activity that cannot be seen as with in situ walkover scanning surveys. Production volumes can range from 80 to 200 cubic yards per hour.

A hallmark of ISO-Pacific’s platform creation strategy is customization. State-of-the-art high-performance detectors are specifically chosen and placed in array formats tailored to the needs of each project. Previous arrays have included options such as specially shaped tungsten wells for each detector; added “shadow” shield flat plates which help to attenuate any photon emissions reaching detectors from the ground below the S3; and methods to ensure the array is temperature controlled and monitored for humidity. ISO understands that developing arrays with the project conditions in mind ensures client savings and no contaminant is missed.

Calibration is performed on site, upon arrival, using the counter manufacturer's automated calibration software. There are no delays associated with waiting for detectors and electronics to be calibrated off site.

All MARSSIM-prescribed quality assurance and quality control directives for the detection system are performed automatically via software algorithms. Human errors and bias have been removed from the equation.

Figure J-3 ISO-Pacific S3 Soil Sorter System

Source: http://isopacific.net/s3/

J.4 SEALAND ENVIRO

SEALAND ENVIRO, LLC
757 Wrights Crossing Road
Pomfret, CT
http://sealandenviro.com/services/radiological-soil-sorting

SEALAND ENVIRO is involved in Superfund radiological site remediation, with particular attention to volume reduction of radiologically contaminated soil utilizing the segmented gate system technology originally developed by Eberline Services, Inc. In 2013, SEALAND ENVIRO completed a comprehensive redesign of the radiological soil segregation system and named it the SGS-4; no figure was available on the company's Web site. The new SGS-4 represents an advanced radiological soil sorting technology. SEALAND ENVIRO is pursuing project opportunities in partnership with prime contractors on projects where volume reduction of radiologically contaminated soils is desired.

J.5 Chesapeake Nuclear Services—CRATER™ Bucket Loader Design

Chesapeake Nuclear Services, Inc.
788 Sonne Drive
Annapolis, MD
http://www.chesnuc.com/

CRATER™ is a specialized radiation detection instrumentation system developed by Chesapeake Nuclear Services (ChesNuc) and Radiation Safety Associates, Inc. The designers claim that through its integration of radiation detector technology with customized spectral analytical methodology, CRATER™ provides a unique analytical solution for identifying elevated levels of radioactive material that may exist in excavated soils during site decommissioning and remediation. Examining the spectral characteristics and factoring in the buildup of the Compton background, the system is capable of identifying constituents with elevated levels for the radionuclide of concern.

The product was designed to support large-area soil remediation and bulk material scanning projects. With spectral capabilities, it is able to analyze specific gamma energies of interest to enhance detection capability and allows sorting and segregating in varying background levels and material compositions. Using real-time data collection, analysis, and Bluetooth communication, CRATER™ is fully capable of supporting automated material processing and handling mechanisms. This product may significantly improve throughput and reduced personnel exposures. Figure J-4 illustrates the placement of the CRATER™.

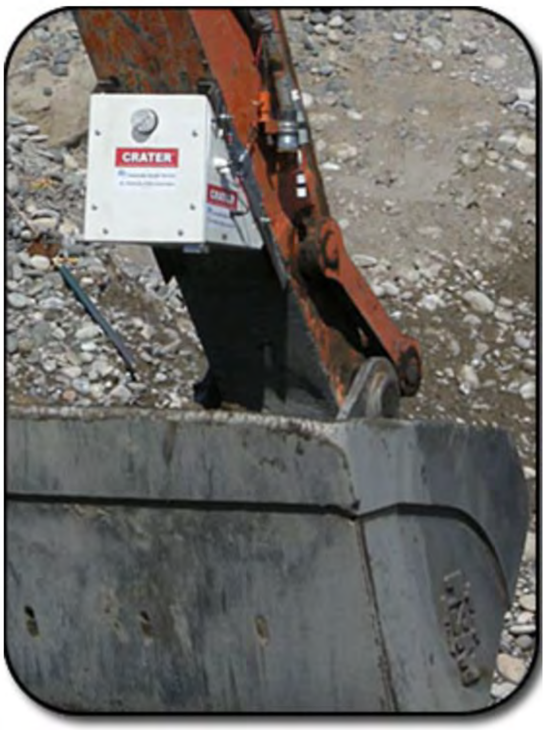

Figure J-4 CRATER™ Installed on Bucket Excavator

Source: Provided by ChesNuc

J.6 Energy*Solutions*—Large Container Assay Systems

Energy*Solutions*
Instrument Services
1570 Bear Creek Road
Oak Ridge, TN
https://instruments.energysolutions.com/instrument-rental/

Energy*Solutions* offers many monitoring systems and instruments, including the GARDIAN III (GAmma Radiation Detector In-container ANalysis) for dry-sacks and larger containers shown in Figure J-5.

Figure J-5 GARDIAN III Large Container Assay System

Source: https://instruments.energysolutions.com/GARDIAN-III/

J.7 Mirion—Large Container Monitors

Mirion Technologies (MGPI) Inc.
Atlanta, GA
https://www.mirion.com/global-office-locations/americas-offices

Mirion offers various gamma measurement systems for the measurement of nonpackaged and packaged waste, as well as containers of different sizes. These systems can be provided in a variety of configurations from standalone, manually loaded systems to fully automated systems that provide greater throughput and minimize personnel exposure. These systems can be provided in a variety of configurations from standalone, manually loaded systems to fully automated systems. Figures J-6 and J-7 present two of Mirion's systems for large item processing.

Figure J-6 WM2400—Large-Volume Decommissioning Counters

Source: https://www.mirion.com/products/wm2400-large-volume-decommissioning-counters

Figure J-7 WM2500—Modular Gamma Box and Container Counter

Source: https://www.mirion.com/products/wm2500-modular-gamma-box-and-container-counter

APPENDIX K

CASE STUDIES

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K.1 Case 1—Scanning Land Survey

K.1.1 Background

Current U.S. Nuclear Regulatory Commission (NRC) practice for remedial work for subsurface areas is to perform gamma ray surveys for designated 6-inch layers at each excavated layer within the pit, or to spread the material in a 6-inch layer outside the pit area and survey or stockpile it for survey later (NRC 2020a).[1] This survey technique requires that at least one of the radionuclides involved be a good gamma emitter (see Table 6.3, "NaI(Tl) Scintillation Detector Scan MDCs for Common Radionuclides and Radioactive Materials," in draft Revision 2 of NUREG-1575, "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)," issued May 2020 (NRC 2020b). As discussed in Section 10, some licensees have used soil-sorting technology for large sites with contaminated subsurface soil in order to produce stockpiles of segregated soils below and above a criterion optimized for maximum refill and minimum waste. Often, the stockpiles are resurveyed after being spread in 6-inch lifts (NRC 2020c). Further, the sidewalls and benches in trenches must often be surveyed, where simply walking on the surfaces could present a physical hazard to a worker.

Draft Revision 2 of MARSSIM permits the use of scanning techniques, with limited physical samples for quality control purposes, for demonstrating that concentrations of radioactive material do not exceed the release criteria.[2] The scan minimum detectable concentration (MDC) and measurement method uncertainty must be sufficient to meet measurement quality objectives to both quantify the average concentration of the radioactive material and to identify areas of elevated activity. In addition, scanning equipment must be coupled with GPS or other locational data equipment. Maintaining the specified source-to-detector distance and speed during scanning can be difficult on irregularly shaped surfaces, so attention to smooth grading is required.

These scanning surveys do require physical samples for validation of the survey meter results. The validation samples will be fewer in number than would be required for a systematic physical sampling campaign, resulting in a lower overall cost. Data validation is used to ensure that the results of the data collection activities support the objectives of the survey as documented in the quality assurance project plan (NRC 2020b), and validation sampling should be considered as quality control. The use of this scanning survey technique should be considered an as low as reasonably achievable (ALARA) technique, as dose would be reduced by not collecting the larger number of samples that would have been needed for a systematic sampling campaign for a Class 1 survey.

Important considerations for a decommissioning or license termination plan that relies on such a scanning approach for scanning of soils removed from an excavation or to be placed in an excavation with only validation sampling for characterization surveys and final status surveys include the following, which are still being addressed by the NRC staff in guidance:

- timing
- approach
- instruments
- percent of area scanned
- addressing challenges to scanning (obstructions or saturated conditions)

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[1] This discussion does not address discrete radioactive particles at this time, pending resolution with respect to work on Revision 2 of MARSSIM.

[2] This example is based on scanning techniques as described in the draft MARSSIM Revision 2. The NRC has not yet incorporated this type of survey design and validation technique into guidance.

- scan speed
- distance between soil and detector
- accessibility of side walls/bottoms
- classification of the excavation/side walls
- number of samples for quality control/validation
- depth of samples
- surveys of excavated soils
- sorting and segregation of excavated soils
- scan distance for survey of excavated soils
- classification of excavated soils

It is important to note that if there is a potential for contamination of the vadose zone beneath the excavation, then soil and ground water sampling should be conducted to understand the potential risk contributions from deep vadose zone or saturated sediments and ground water. In this case, a survey approach that relies heavily on scan survey measurements of the deep subsurface would likely be inappropriate. Much of the discussion in this case study example pertains to soils that are removed from an excavation and are being characterized for potential reuse.

However, one case study cannot completely address the topics above. For example, DCGLs are assumed here, and stepping through the DCGL selection process would detract from part of the case objective to introduce innovative survey and validation approaches and to further explore recent tools like the software Spatial Analysis and Decision Assistance (SADA) for visual analysis of survey results. While innovative approaches are freely discussed and encouraged in this white paper, not all of the approaches have been fully vetted and peer reviewed; therefore, additional work may be needed to incorporate proposed methods into NRC guidance, if deemed to be beneficial to the decommissioning process and of interest to NRC licensees.

K.1.2 Case Scenario

This case involves a fictitious site where the licensee has stockpiled soil excavated from the subsurface during remediation and wishes to use it as backfill. The sidewalls and benches in trenches, which often present a physical hazard to workers, have already been surveyed and those surveys are not part of this case. The excavated soil has a history of cesium (Cs)-137 contamination, based on earlier characterization samples, at concentrations above the NRC's surface soil screening derived concentration guideline level (DCGL) of 11 picocuries per gram (pCi/g) in Table H.2 of Appendix H to NUREG-1757, Volume 2, Revision 2, "Consolidated Decommissioning Guidance, Characterization, Survey, and Determination of Radiological Criteria, Draft Report for Comment," issued November 2020 (NRC 2020c). Site-specific dose modeling simulations show that the surface soil screening levels are protective for reuse of soil at the expected depth and thickness of backfill soils. The licensee plans to use the material as backfill to grade to ground surface; however, the licensee does not want the average concentration to meet the DCGL but would rather survey and remove any suspect volumes above the DCGL. The licensee decided that elevated areas/volumes above the DCGL would be removed and packaged for disposal at an offsite authorized location.

The stockpiled soil from the subsurface has been spread with a thickness of 6 inches over a 50-meter (m) by 40-m area. The soil is a typical silty soil containing 30 percent water and

20 percent air by volume with a density of 1.6 grams per cubic centimeter (cm^3).[3] The purpose of the survey is to assess the radiological levels in the excavated soils for Cs-137 with a cleanup level of 11 pCi/g.

This case study illustrates a scanning survey with approaches from MARSSIM, draft Revision 2; its Supplement 1, "Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME)," issued January 2009 (NRC 2009)[4]; and NUREG-1507, Revision 1, "Minimum Detectable Concentrations with Typical Radiation Survey for Instruments for Various Contaminants and Field Conditions," issued August 2020 (NRC 2020a). It also demonstrates the use of the software packages MicroShield and SADA and the techniques of the U.S. Environmental Protection Agency's (EPA's) ProUCL. Further, it discusses a novel approach to reduce background levels by shielding detectors.[5] The novel techniques illustrated are applied in part to improve MDCs; these reduced MDCs in turn permit a scanning survey that might otherwise require both scanning and costly systematic sampling (rather than just verification samples). Although this case concerns the scanning of soil from a stockpile of excavated material, much of the discussion could apply to scanning surveys of surface soil or an excavation bench or bottom, although depending on the contamination potential of the soils located below the excavation, sampling of the soils and ground water below the excavation may also be necessary.

As with other survey approaches, the licensee's survey planners are responsible for developing the survey plan with data quality objectives (DQOs) and measurement quality objectives and interpreting the results. This case study presents some survey design issues and required decisions anticipated in the field, including one example of how validation sample results may be performed and verified by the licensee with the aid of an NRC inspection procedure. It does not address the challenges to scanning (obstructions or saturated conditions), inaccessibility of sidewalls, and the classification of sidewalls, as these will be specific to each site.

K.1.3 Scan Technique for Land Areas

Conducting a survey requires use of an appropriate scanning speed and elevation of the detector above the ground or grass. Scanning surveys should be conducted using a slow walk. The generally accepted industry practice is that gamma scanning should be performed by swinging the detector in front of the body in a pendulum manner while progressing at the speed of a slow walk. These gamma walkover surveys are usually performed by swinging the radiation detector (e.g., a 2-inch by 2-inch thallium-activated sodium iodide (NaI(Tl)) scintillation detector) in a serpentine pattern at a near constant height above the ground surface (10 centimeters (cm), including grass height) with a swing speed of 0.5 m per second (s) and a walking speed of 0.25 m/s. The objective is to survey an approximately 1-m swath with 100-percent coverage (i.e., a Class I area), producing an equal probability of detecting contamination at any point along the swing (King et al. 2012).

Figure K-1 illustrates the implementation of this concept for a typical elevated area, as defined in MARSSIM Revision 1, issued August 2000 (NRC 2000a), which is presented as the highlighted circle with a diameter of 56 cm. The dotted line indicates the path of the detector center, which should cross the elevated area twice. MARSSIM further describes how to

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3 This mirrors the source term for external exposure from Federal Guidance Report No. 12, "External Exposure to Radionuclides in Air, Water, and Soil," issued September 1993 (EPA 1993).

4 MARSAME summarizes the survey application on pages RM-3 and RM-4, with full description in Section 4.

5 Although such shielding devices are commercially available, this approach is described here for example purposes only and has not been endorsed by the NRC.

investigate when an elevated area is discovered. This case study will rely on geographic information system (GIS) plotting shown later.

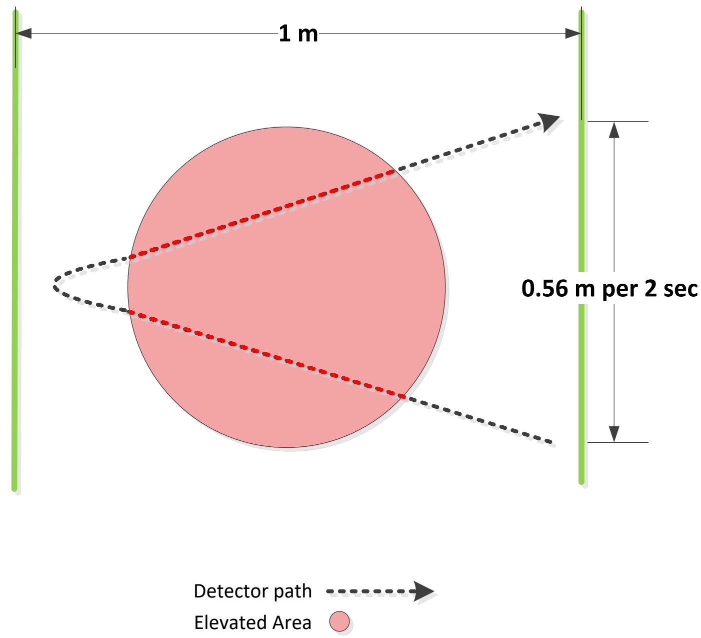

Figure K-1 Illustration of Scan Path

The required scan coverage is determined based on the survey unit classification and other parameters, such as the site's radiological history, contamination potential, and findings as the survey progresses. Because MARSSIM Revision 1 indicates that Class 1 areas will require high-density scans (100 percent), the walkover scan intervals should be 1 m wide, as shown in Figure K-1. MARSSIM Revision 1 indicates that surface scans are performed over 10 to 100 percent of open land surfaces for Class 2 areas and over an appropriate percentage as judged by the planners for Class 3 areas (NRC 2000). The final version of MARSSIM Revision 2 should be consulted for potential changes to the recommended scan percentage. Ideally, a survey of a Class 1 unit of 2,000 square meters (m^2) would require about 133 minutes (just under 2.25 hours) of survey time without any stopping to assess the presence of an elevated area.

K.1.4 Minimum Detectable Count Rate

This case study requires a scan minimum detection count rate (MDCR) for Cs-137 with its short-lived progeny, barium (Ba)-137m, using a 2-inch by 2-inch NaI(Tl) scintillation detector. The normal background level is 9,250 counts per minute (cpm). Commercial lead collimators are available (see Figure K-2(a)), but the survey crew placed a 1/8-inch-thick piece of 6-inch-long lead around the detector, adding about 1 pound to the detector weight and reducing the background to about 7,000 cpm.[6] Figure K-2(b) illustrates the wrapping of a 2-inch by 2-inch detector with lead, leaving the bottom uncovered. The NRC is aware of this practice being used in the field but to date has not identified peer reviewed papers evaluating it further.

[6] Without lead shielding, it is estimated that 75 percent of the background count rate is from photons entering the top and side of the NaI crystal; with lead shielding of the side and shadow shielding of the top, an overall reduction factor of background is estimated to be about 0.76.

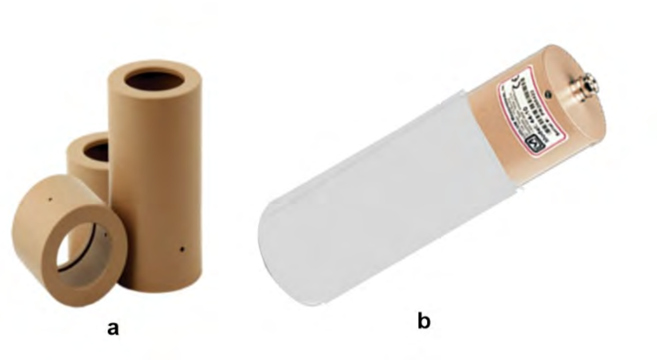

Figure K-2 Lead Collimators and a Lead-Wrapped 2x2 Detector

Source: (a) Ludlum Measurements, Inc. and (b) a modified Ludlum 44-10 detector

DQOs determined at the planning stage of the survey established the desired level of performance,[7] *d′*, of 95-percent correct detections and a 60-percent false positive rate. For those values, Table 6-2 in MARSSIM, draft Revision 2, gives an index of sensitivity of 1.38. The scan rate (swing speed) of 0.5 m/s with a walking speed of 0.25 m/s provides the observation interval of 1 s (based on the MARSSIM elevated area concept, which uses a diameter of about 56 cm for a small area of elevated activity). The ideal observer's MDCR, in cpm, can be calculated using Equation K-1:

$$MDCR = d' \times \sqrt{b_i} \times \left(\frac{60}{i}\right) \qquad \text{(Eq. K-1)}$$

where:

MDCR = minimum detectable (net) count rate for the ideal observer in cpm

d′ = the index of sensitivity

b_i = background counts in the observation interval

i = observational interval (in seconds), based on the scan speed and areal extent of the contamination

For this case—

$$MDCR = 1.38 \times \sqrt{7{,}000/60} \times \left(\frac{60}{1}\right) = 890 \text{ cpm}$$

K.1.5 Modeling Using MicroShield

The net exposure-rate-to-concentration ratio (ERC) (microroentgen per hour (μR/h) per pCi/g) is established through modeling with an objective to determine the radionuclide concentration that is correlated to the minimum detectable net exposure rate. The MARSSIM guidance for an elevated activity volume is used and consists of a cylindrical area of elevated activity of 0.25 m^2 (radius of 28 cm) with a depth of the area of elevated activity as 15 cm. Tables K-1 and K-2 show the parameters selected for this case. The net exposure rate per pCi/g was modeled using MicroShield version 8.02 (Grove 2008). Figure K-3 shows the dimensions as entered into

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7 An index of sensitivity (d') represents the distance between the means of the background and background plus signal caused by residual contamination (see MARSSIM Section 6).

MicroShield; note that the dose point height Y in Figure K-3 is measured from the bottom of the elevated cylinder.

The ERC developed from the MicroShield analysis for this example is about 0.25 µR/h per pCi/g.

Table K-1 Case Study Parameters

Parameter	Value
Survey unit class	Class 1
Detector	2-inch by 2-inch NaI(Tl) scintillation detector
Scan height	10 cm (average)
Contaminated area	0.25 m^2, radius 28 cm (diameter 56 cm)
Radionuclide of concern	Cs-137 with Ba-137m
Concentration	1 pCi/g
Depth of elevated activity	15 cm
Soil composition	Silty soil, 30% water and 20% air by volume
Soil density	1.6 grams per cm^3

Table K-2 Soil Composition

Element	Mass Fraction
H	0.021
C	0.016
O	0.577
Al	0.050
Si	0.271
K	0.013
Ca	0.041
Fe	0.011
Total	1.000

Source: EPA 1993

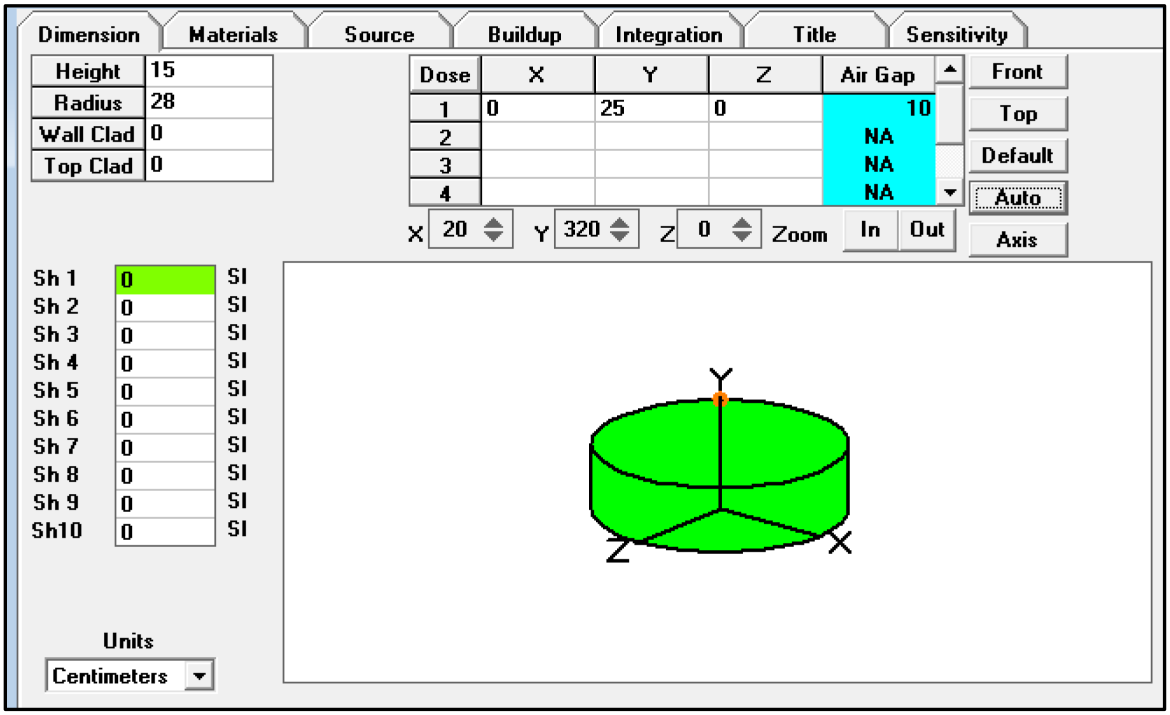

Figure K-3 Definition of Small Area of Elevated Activity Using MicroShield Version 8.02

Source: MicroShield graphic

K.1.6 Scan Minimum Detectable Concentrations for Land Areas

The form of the generic *a priori* scan MDC is defined in MARSAME and NUREG-1507 and presented in Equation K-2:

$$\text{Scan MDC} = \frac{MDCR}{\sqrt{p} \times CPMR \times ERC} \qquad \text{(Eq. K-2)}$$

where efficiencies (count-rate-to-exposure-rate ratio (CPMR) and ERC) are used to convert the MDCR in cpm to a quantity that is directly comparable to a cleanup goal (e.g., pCi/g for soil). Of the terms in Equation K-2, the instrument efficiency is either known (e.g., from the literature) or calculated. For this case, the manufacturer of this particular scintillation detector quotes a CPMR for Cs-137 of 900 cpm per µR/h. As calculated in Section K.1.3, the ERC (source efficiency) was determined to be 0.25 µR/h per pCi/g. Further, as shown in Equation K-2, the scan MDC is also modified by the surveyor efficiency, *p*, which is estimated considering human factors, as described in the following paragraph.

To adjust an estimated scan MDC to reflect an assumed surveyor efficiency, the square root of the efficiency is applied to provide a surveyor-specific scan MDC. The surveyor efficiency in accordance with NUREG-1507 is, as a rule, no greater than 0.75, but an efficiency value of 0.5 is an appropriate default for estimating field performance. Since this case is for a Class 1 area, the survey plan would specify that 1-meter survey lanes will be established over the survey area, giving surveyors visual lane references. Selecting a *p* of 0.75 would be considered justified for this site as the performance of the survey team is assumed to be close to ideal, given the empirical data available for the site and established controls (NRC 2020a).

For this case study, the scan MDC for the stated conditions is calculated using Equation K-2 as shown below:

$$\text{Scan MDC} = \frac{890\ cpm}{\sqrt{0.75} \times 900 \frac{cpm}{\mu R/h} \times 0.25 \frac{\mu R/h}{pCi/g}} = 4.6 \text{ pCi/g}$$

The scan MDC compares favorably to that in Table 6-3 of MARSSIM, draft Revision 2, on NaI(Tl) scintillation detector scan MDCs for common radiological contaminants, which listed 6.4 pCi/g as a scan MDC for Cs-137 but applied a more conservative background of 10,000 cpm and a surveyor efficiency of 0.5.

Both MARSSIM Rev. 1 and draft Rev. 2 requires the scan MDC should be below the DCGL—preferably at a fraction (approximately 50 percent) of the DCGL.[8] Other measurement quality objectives, such as requirements for measurement method uncertainty, must be established and met.

K.1.7 Plotting Scan Results with SADA

As noted in Section K.1.1, in this case study, global positioning system (GPS)-enabled gamma walkover scans were conducted across the Class 1 survey unit as part of this final assessment. These were performed by slowly moving the NaI detector across the surface at approximately 0.5 m/s at a height of 10 cm.

As illustrated in Figure K-4, the hypothetical[9] investigation was conducted along a series of traverses spaced at 1 m apart across the field waste spreading area. Each radiation reading and its position were logged. Data gathered during the gamma walkover survey were used to generate a color map depicting radiation levels recorded along each transect. This map is used to show coverage of the transects and to visually compare the radiation levels recorded on site to those recorded in background locations. Note that the color maps can be misleading if the GPS unit is not directly centered over the survey path (i.e., if the sensor is placed over one shoulder versus the head, the scan paths may appear to be closer or farther away from the previous path depending on the direction of turn). In this case, the GPS sensor was always in the center of the walking path.

MARSSIM, draft Revision 2, addresses the concern for small areas of elevated activity by using a simple comparison to an investigation level as an alternative to statistical methods. Using the elevated measurement comparison (EMC) is a conservative approach because additional investigation is required unless every measurement is below the investigation level. For Class 1 survey units, the investigation level for this comparison is called the $DCGL_{EMC}$. The $DCGL_{EMC}$ can be higher than the $DCGL_W$ due to the lower dose or risk resulting from a smaller area of radioactive material. In the case of multiple areas of elevated activity in a survey unit, a posting plot of the distribution of activity in the survey unit can be used to determine any pattern in the location of these areas (NRC 2020b).

The posting plot in Figure K-4 clearly demonstrates that a portion of the area in the southeast corner is contaminated above the $DCGL_W$. In this case study, the site owner agreed to remove all identified contamination above 5 pCi/g, meaning that the measurement areas shown in yellow and red in Figure K-4 would be excavated and the material packaged for shipment to an authorized offsite burial site. Note that in this case, validation samples were collected before remediation.

8 MARSSIM, draft Revision 2, is currently in preparation, and the final version may change this MDC recommendation of 50 percent $DCGL_W$ to a higher or lower fraction of the DCGL. The final version of MARSSIM Revision 2 should be consulted.

9 GPS coordinates were changed to grid coordinates for anonymity of the landowner.

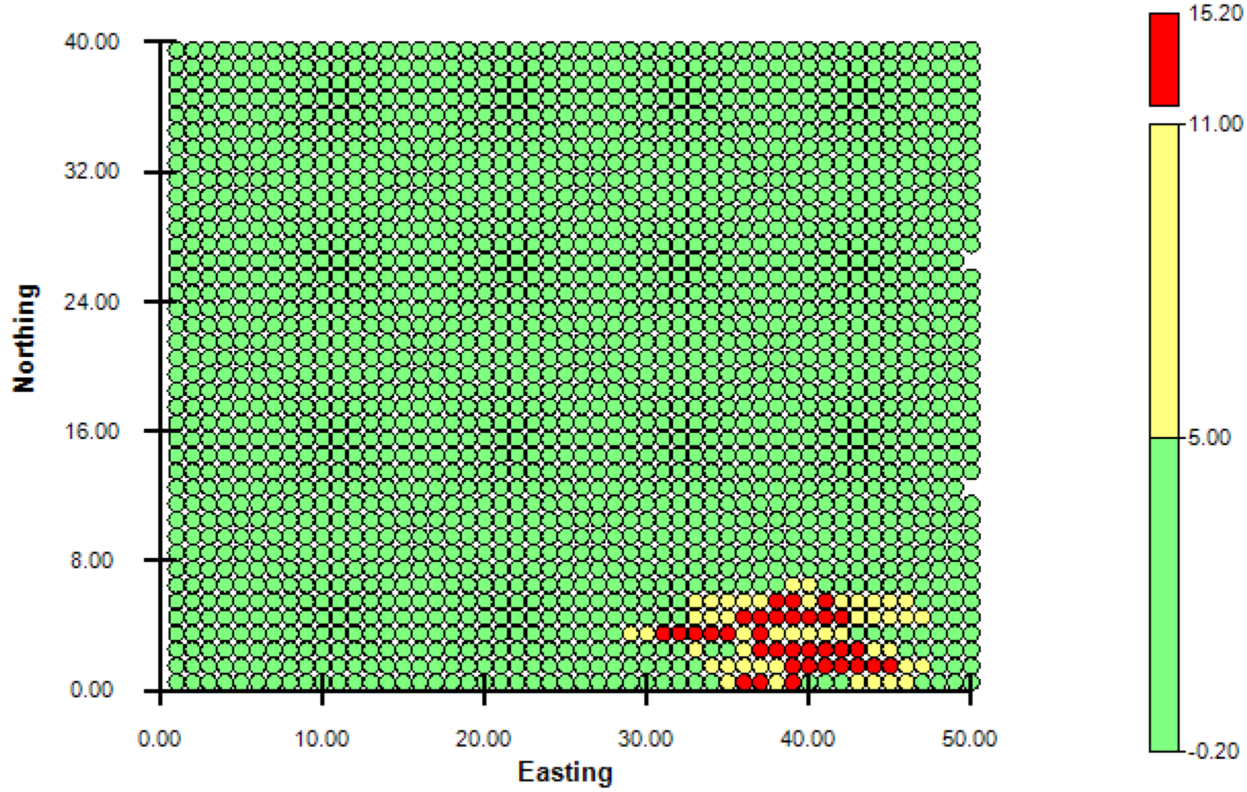

Figure K-4 Plot of Gamma Scan Results (pCi/g) Using SADA Version 5

Notes: Dimensional units are meters

Recognizing that surgical removal of just the soil above the DCGLw was impossible, the licensee anticipated that the actual remediation would require excavation of nearby soils level probably down to a 5 pCi/g level. As the elevated material was removed, there was no need to perform additional elevated measurement testing, and no credit was taken for an EMC based on the size of the elevated area compared to the survey unit overall.

K.1.8 Development of an Upper Confidence Limit

Because this case represents a scanning survey, it does not include systematic sampling and direct measurements, except for those required for validation and comparison to a UCL. With a scanning survey, the UCL for the mean derived from the arithmetic mean, the variance, and the number of the measurements represents the parameter of interest for demonstrating compliance.

Section 8.5 of MARSSIM, draft Revision 2, provides instructions to generate a UCL when a large number of measurements are taken (in a scanning survey). A one-tailed version of Chebyshev's inequality or a software application (e.g., EPA's ProUCL) can be used to evaluate the probability of exceeding the upper bound of the grey region using a UCL (NRC 2020b). These statistical approaches are examined extensively in EPA/600/R-07/041, "ProUCL Version 5.0.00 Technical Guide, Statistical Software for Environmental Applications for Data Sets with and without Nondetect Observations," issued September 2013 (EPA 2013).

The concentration of Cs-137 in surface soil from fallout ranges from about 0.1 to 1 pC)/g, averaging less than 0.4 pCi/g (ANL 2007). Because the levels in background are a small fraction of the DCGL, no credit for background was taken, all measured concentrations were considered as being from facility operations, and no reference area measurements were deemed necessary.

Chebyshev's inequality calculates the probability that the absolute value of the difference of the true but unknown mean of the population and a random number from the data set is at least a specified value. That is, given a specified positive number (n), a mean (μ), and a random number from the data set (r), then the probability that $[\mu - r]$ is greater than or equal to n is equal to α. In addition, a one-tailed version of the inequality can be used to calculate a UCL for a data set that is independent of the data distribution (i.e., there is no requirement to verify the data are from a normal, lognormal, or any other specified kind of distribution) by letting the inequality equal the UCL. The UCL can also be calculated using Equation K-3:

$$\mathrm{UCL} = \mu + \sqrt{\frac{\sigma^2}{n\alpha} - \frac{\sigma^2}{n}} \qquad \text{(Eq. K-3)}$$

The following steps describe the comparison to the UCL:

(1) Calculate the mean (μ) and standard deviation (σ) of the number of results (n) in the data set.

(2) For MARSSIM Scenario A, retrieve the Type I error rate (α) used to design the survey.

(3) Using Chebyshev's inequality, calculate the maximum UCL using Equation 3.

For this case study, following removal of the contaminated area discovered during scanning and related scanning data points from the initial scanning data set, the remaining data set has a mean (μ) of 0.015 pCi/g and a standard deviation (σ) of 0.26 pCi/g, and the number (n) of results was 1,914. The acceptable error (α) was set during survey planning at 0.05. The UCL for the remaining site data was determined from Equation K-3:

$$\mathrm{UCL} = 0.015 + \sqrt{\frac{0.26^2}{1914 \times 0.05} - \frac{0.26^2}{1914}} = 0.04 \text{ pCi/g}$$

The use of the UCL applies for scanning surveys where individual results are recorded. When release decisions are made about the estimated mean of a sampled population, the assessment of the survey results is accomplished by comparing a UCL for the mean to the $\mathrm{DCGL_W}$. For MARSSIM Scenario A as applied to this example, if the UCL is less than $\mathrm{DCGL_W}$, then the survey unit meets the average release criteria and the Elevated Measurement Comparison test is applied as appropriate. If the UCL is greater than the $\mathrm{DCGL_W}$, the survey unit does not meet the release criteria. For this case, the $\mathrm{DCGL_W}$ was selected as 11 pCi/g for Cs-137 from the NRC's lookup table value from Table H.2 in NUREG-1757, Volume 2, Revision 2, with surface soil screening values (pCi/g) of common radionuclides for soil surface contamination levels, after confirming that the screening level was protective based on site-specific simulations with the expected depth and thickness of backfill soils. As the UCL is less than the release criterion, the survey demonstrates compliance with the disposition criterion (i.e., reject the null hypothesis for the scenario).

K.1.9 Scanning Replication

Replicate measurements are measurements performed at the same location to provide an estimate of the random uncertainty for the measurement method. The reproducibility of measurement results should be evaluated using replicates to establish this component of measurement uncertainty (see MARSSIM, draft Revision 2, Section 6.4). For scanning surveys, where decisions are made based on logged and geolocated measurements, typically 5 percent of all measurements are replicated (e.g., 5 percent of the scanned area is scanned twice) (NRC 2020b). The rescanned areas for this case study produced a mean within 5 percent of the original, which was deemed acceptable without further analysis.

K.1.10 Collection of Validation Samples with Z-Scores

Scanning surveys require site-specific validation samples to ensure that the method can reliably detect concentrations at the $DCGL_W$ under the conditions expected at the site.

As indicated in Section 2.5 of the main report, NUREG-1507, Revision 1, presents concepts related to GPS/GIS-based techniques and methodologies, along with considerations for detection efficiency calculations, background interferences, signal degradation, and other topics associated with radiation survey instrumentation. GIS technicians map captured data by using, for example, binning and color-coded plots to show locations of radiological contamination, as illustrated in Figure K-4 for this case study. Statistical analyses to determine the investigation level for which followup measurements are advisable can be made using free analysis software for univariate statistics, such as SADA (Stewart et al. 2009), Visual Sample Plan (VSP) (Matzke et al. 2014), and ProUCL (EPA 2013).

Considerations to develop an investigation level *a posteriori* for postprocessed data (IL_{PP}) are provided below, using a z-score to establish them (NRC 2020a). Decommissioning projects should select an IL_{PP} that best satisfies site-specific requirements (such as DQOs and regulatory approvals). In this case study, the background population is assumed to be normally distributed. As presented in Section 2.5 of the main report, the z-score is calculated as follows:

$$z = \frac{X-\mu}{\sigma} \qquad \text{(Eq. 4)}$$

where:

X = the data point value
μ = the background population mean
σ = the background population standard deviation

As an example, a z-score is calculated for the highest result obtained from scanning, where X = 15.2 pCi/g, μ = 0.41 pCi/g, and σ = 2.01 pCi/g. Substituting these values into Equation K-4 yields the highest z-score:

$$z = (15.2-0.41)/2.01 = 7.4$$

The NRC has developed a mechanism for comparing laboratory analytical results and determining the acceptability of licensee measurements (NRC 1985). The NRC technique has been adopted by licensees for internal reviews for samples analyzed on site and then compared to duplicate sample results from off site as a data quality indicator. For this case, the site's laboratory results and uncertainty will be substituted in the NRC's resolution formula, Equation K-5. The acceptance criteria are a function of the resolution in accordance with Table K-3.

$$\text{Resolution} = \frac{NRC\ value}{NRC\ uncertainty} \qquad \text{(Eq. K-5)}$$

Table K-3 Criteria for Accepting the Licensee's Measurements

Resolution	Ratio
<4	0.4–2.5
4–7	0.5–2.0
8–15	0.6–1.66
16–50	0.75–1.33
51–200	0.80–1.25
>200	0.85–1.18

Source: NRC 1985, page 4

In this case study, DQOs were established to require a range of locations with positive z-scores to define where validation samples were to be collected. The range of positive scan results selected for validation was from 2.4 to the maximum of 15.2 pCi/g; these correspond to z-scores from 1 to the maximum of 7.4 as determined using Equation K-4. The soil samples collected for validation purposes were analyzed by the site's laboratory, and Table K-4 shows the results of the evaluation. As shown in Figure K-4, all elevated results, indicated in the figure by the concentrations shown in yellow and red, occurred in the southeast portion of the survey unit, and validation samples were collected before removal of the elevated soil. All ratios developed in Table K-4 were within the acceptable ranges shown in Table K-3.

Table K-4 Validation Analysis of Scan versus Laboratory Results

Scan	Onsite Laboratory			
Concentration (pCi/g)	Concentration (pCi/g)	Uncertainty (pCi/g)	Resolution	Ratio
15.2	16.3	1.95	8	0.93
10.2	11.7	1.5	8	0.87
8.4	9.3	1.3	7	0.90
5.1	5.0	0.8	6	1.02
2.4	2.0	0.35	6	1.22

Valid data are all data that are usable, including data with no validation qualifiers and estimated data that are justifiable for use (NRC 2020b). For this case study, although one of the selected scan samples was below the scan MDC, measurements were determined to be valid through the measurement range.

K.2 Case 2—Modeling Buried Material Using Geostatistical and Shielding Codes

Decommissioning planning involves several considerations, such as the timeliness of decommissioning as to when it should occur, future use of the land, plausible use and intrusion scenarios, and controlling expenses. Potential exposures to members of a critical group[10] must be considered. The presence of buried material at a site introduces an additional element of complexity.

This case study considers a site with buried material. The facility license and operations included a single radionuclide of concern, Cs-137. For all dose assessments, the Cs-137 progeny Ba-137m is assumed to be in equilibrium. For the bounding scenario, which must be selected based on reasonably foreseeable land use, the site managers, owner, and other

[10] The term "critical group" means the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances (Title 10 of the *Code of Federal Regulations* (10 CFR) 20.1003, "Definitions").

interested parties have decided to use a resident farmer scenario that also considers human intrusion into buried radioactive material during excavation for a basement and drilling for a well. A resident farmer is the average member of the critical group for development of soil DCGLs. The hypothetical residence and farm are assumed to be located on a part of the project premises impacted solely by the subsurface radioactivity, including that brought to the surface during house basement excavation. This resident farmer scenario is considered to bound the potential dose to house construction workers, due to their limited exposure time. The same conclusion could be reached for the well driller; however, for a more thorough examination and documentation of exposure scenarios, the dose to a well driller is included.[11]

This case study includes a review of subsurface characterization through GIS and geostatistical tools to analyze and identify areas most likely to be above risk-based thresholds. This is consistent with the approach laid out in NUREG/CR-7021, "A Subsurface Decision Model for Supporting Environmental Compliance," issued January 2012 (NRC 2012).

For a site-specific analysis, the NRC's DandD code and the RESRAD-ONSITE code[12] may be used, in addition to other codes (NRC 2020c). For this case study, subsurface DCGLs are developed with the RESRAD-ONSITE code using certain DandD default parameters to align with parameters used to develop screening levels in NUREG-1757, Volume 2, Revision 2, Appendix H. MicroShield is used for assessing potential doses resulting from direct exposure to the subsurface and the redistributed excavated soils from the house construction. The geostatistical tools available in SADA are used to analyze data and extrapolate data in areas where no or limited data are available.

K.2.1 Development of Conceptual Models and Scenarios

Figure K-5 illustrates the general process for the dose modeling described in this section, which involves the following steps:

- Calculate the DCGLs, using RESRAD where suitable complemented by direct exposure modeling, in the deterministic mode to produce the initial base cases.
- Perform parameter sensitivity analyses and refine the conceptual models and the DCGLs as appropriate based on the results.
- Perform a probabilistic uncertainty analysis to evaluate the degree of conservatism in model input parameters, producing probabilistic peak-of-the-mean and 95th percentile DCGLs.
- Evaluate alternative conceptual models, including a residential gardener and a multisource conceptual model for subsurface soil DCGLs, for comparison with the initial base-case models.

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11 It is important to note that the basement excavation typically dominates the dose compared to the well driller scenario, if the residual radioactivity is located within approximately 3 m of ground surface (i.e., the nominal depth of basement excavation). The well drilling scenario may become important for residual radioactivity located deeper than a nominal 3 m, considering erosion, due to the potential in a well drilling scenario to bring residual radioactivity at depth to the surface that otherwise would not become surface contamination. Construction of a residence on top of the contaminated drill cuttings is typically considered. Both scenarios (basement excavation and well drilling) should be considered to ensure bounding assessments. Other site-specific scenarios that may be viable and more limiting should also be taken into account.

12 RESRAD-ONSITE is a computer model designed to estimate radiation doses and risks from residual radioactive materials (Yu et al. 2001).

- Evaluate the DCGLs produced by all of the modeling and determine the most limiting DCGLs for each radionuclide of interest.
- Analyze combined source area exposure scenarios.
- Consider the results of an ALARA analysis.
- Establish cleanup goals (target levels below the DCGLs).
- Characterize surface soil and subsurface soil.
- Refine the DCGLs and cleanup goals based on the resulting data.
- Complete remediation of the subsurface and selected surface soil areas to the cleanup goals.

This hypothetical case study follows much of the process in Figure K-5 through the first phase of decommissioning beyond initial planning. Parameter sensitivity and probabilistic analyses can be used to identify key parameters most affecting dose and to focus data collection efforts. Either probabilistic or deterministic approaches can be taken to derive DCGLs. For simplicity in illustrating an approach for subsurface contamination, conservative, bounding assumptions are made so as to yield conservative dose results, thereby eliminating the need to perform sensitivity and uncertainty analysis. In either case, risk-significant parameters should be identified, and adequate support provided. The NRC lays out other acceptable approaches for demonstrating compliance with decommissioning criteria in NUREG-1757, Volume 2, Revision 2.

Three exposure scenarios are identified:

(1) resident farmer with house built atop the contaminated zone (CZ) and a well through the CZ

(2) resident farmer with house/basement into the CZ

(3) well driller exposure while drilling a well through the CZ

NUREG-1757, Volume 2, Revision 2, Appendix J, provides guidance on scenario evaluation. Except for certain DandD parameters discussed later, this case study uses the RESRAD ONSITE default modeling, recognizing that actual site parameters must be used for real sites (NRC 2020c).

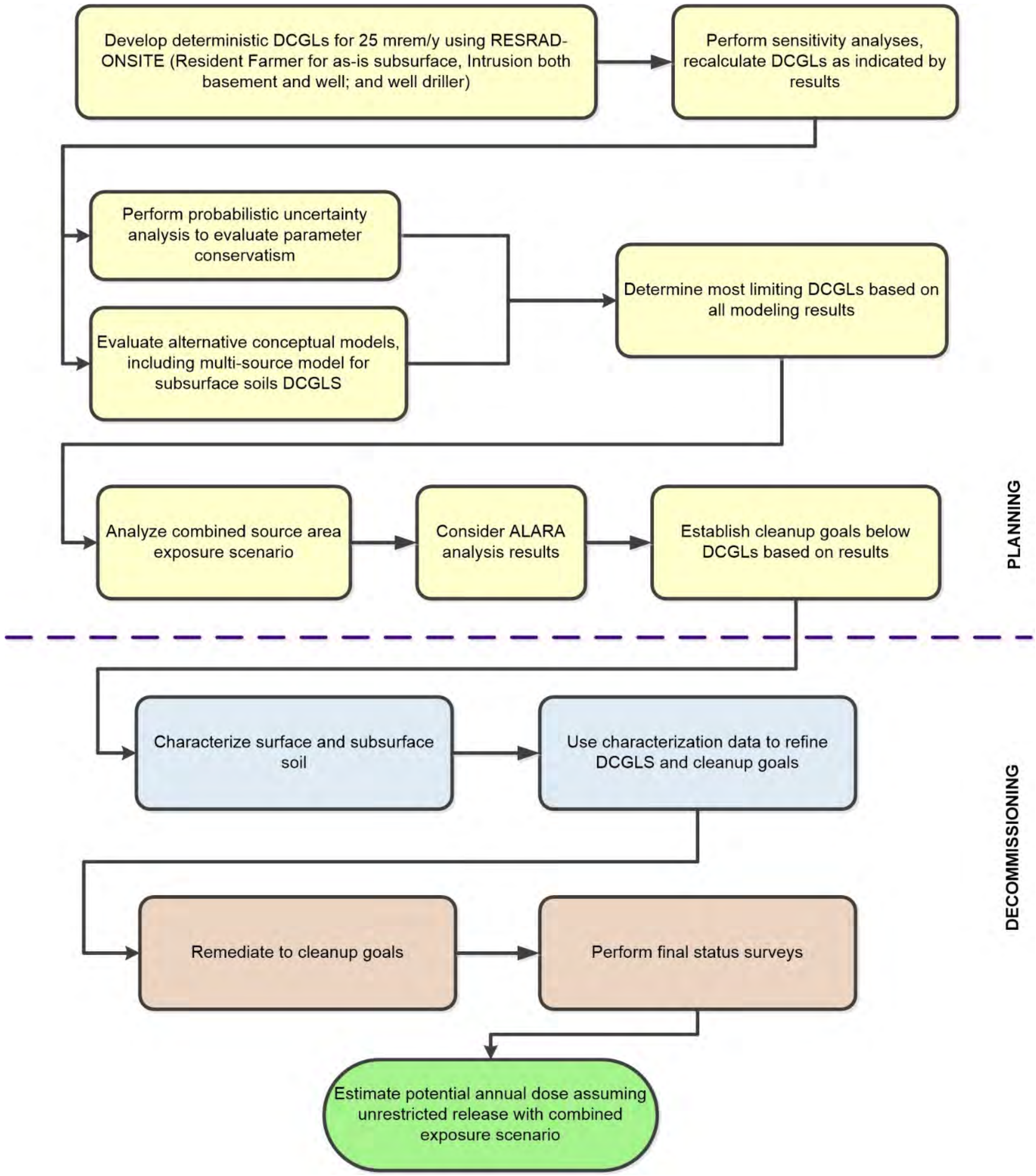

Figure K-5 General Dose Modeling Concepts

Source: Modified from DOE 2009, Figure 5-6

As a general overview, the resident farmer scenarios are evaluated using RESRAD-ONSITE. Figure K-6 shows the exposure pathways. Radon is excluded from consideration under the License Termination Rule primarily because of the difficulty in distinguishing radon resulting from site activity from background radon. In addition, it is difficult to predict design features of future building construction, which will greatly affect the doses someone will receive (NRC 2000b). Although not all the source term is in the original position, leaching will occur both from the remaining buried residual radioactivity and any residual radioactivity that has been moved to the surface due to basement construction (Yu 2012). As illustrated in Figure K-6, the following exposure pathways are considered; aquatic foods are not considered applicable:

- external gamma
- inhalation
- plant ingestion
- meat ingestion
- milk ingestion
- drinking water ingestion

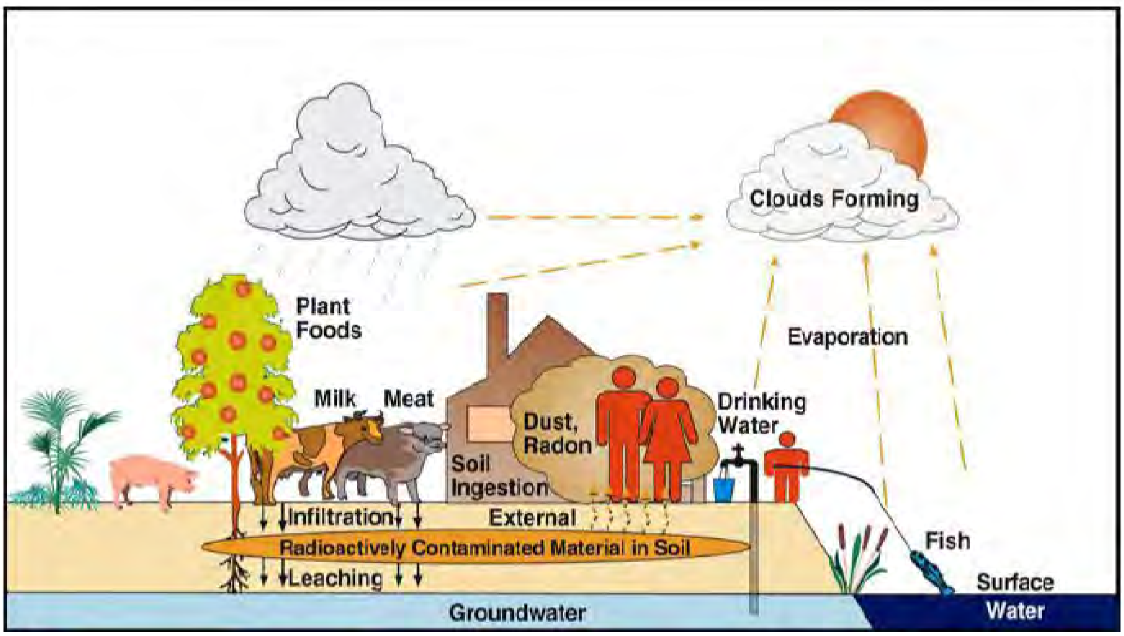

Figure K-6 Exposure Pathways for Resident Farmer

Source: Yu 2012

Although RESRAD ONSITE has default parameters, NUREG-1757, Volume 2, Revision 2, indicates that these parameters are not suitable for use without justification and that default behavioral and metabolic parameters available in DandD (see NUREG/CR-5512, Volume 3, “Residual Radioactive Contamination From Decommissioning, Parameter Analysis,” issued October 1999) can be used with minimal justification. Therefore, for this case study, the listings in Table K-5 for RESRAD ONSITE default parameters were changed to the DandD default parameters.

Table K-5 RESRAD-ONSITE and DandD Default Values

Parameter	RESRAD-ONSITE Default[a]	DandD Default[b]	Units
Inhalation rate	8,400	1.169×10^{4}	m^3/y
Mass loading for inhalation	0.0001	3.14×10^{-6}	g/m^3
Fraction of time spent indoors	0.5	0.6571	
Fraction of time spent outdoors	0.25	0.1101	
Fruits, vegetables, and grain consumption	160	112	kg/y
Leafy vegetable consumption	14	21.4	kg/y
Milk consumption	92	233	L/y
Meat and poultry consumption	63	65.1	kg/y
Soil ingestion	36.5	18.26	g/y
Livestock fodder intake for meat	68	27.1	kg/d
Livestock fodder intake for milk	55	63.25	kg/d
Growing season for nonleafy vegetables	0.17	0.25	y
Growing season for leafy vegetable	0.25	0.123	y
Growing season for fodder	0.08	0.15	y
Storage time for livestock fodder	45	0	d

[a] Yu et al. 2001
[b] NRC 1999

K.2.2 Resident Farmer: No Intrusion with Well

This scenario addresses a resident farmer who digs a well through the CZ. Two steps are needed for this evaluation: (1) exposure to the resident living atop the subsurface CZ and (2) exposure to well cuttings from a well dug through the CZ and dispersed around and under the house. No other intrusion into the CZ is assumed.

Step 1: Exposure to Resident Farmer from Subsurface Contaminated Zone

This RESRAD-ONSITE simulation of the scenario of farming with no intrusion uses the DandD parameters shown in Table K-5 as well as those presented in Table K-6. The size of contaminated surface area was set to coincide with the intrusion scenarios discussed later.

Table K-6 RESRAD-ONSITE Input Parameters for No Intrusion

Parameter[a]	Input
Contaminated subsurface area (m^2)	4,000
Cover or cap (m)	2
Portion of CZ thickness (m)	4
Unsaturated zone thickness (m)	4
Initial concentration (pCi/g)	1
Contaminated layer (m)	4

[a] Except as noted in Table K-5, RESRAD-ONSITE parameters were set to default for convenience.

For this situation with no intrusion, the house is built at ground surface, crop root depth does not penetrate into the CZ, and migration into the saturated zone does not occur. Provided the contaminated soil remains isolated from the biosphere, there are essentially no pathways of exposure.

RESRAD-ONSITE calculated an annual dose of 4.33×10^{-13} mrem/year, with this dose occurring at t = 0 from the ground exposure (direct radiation) pathway. All other pathways had zero contribution.[13] The corresponding DCGL for a 25-mrem dose is 5.8×10^{13} pCi/g. These values show that with the isolation of the subsurface soils (2 m clean cover and above the saturated zone), there is essentially no radiation dose to an individual. Two primary contributors to this result are (1) an assumed 2 m clean cover with an erosion rate (0.001 m/y) that does not significantly reduce the shielding considering the 30-year half-life for Cs-137 and (2) a relatively high distribution coefficient (k_d) for Cs-137, with no breakthrough to the saturated zone anticipated given its half-life of 30 years. Caution is warranted where surface erosion could expose the subsurface CZ and/or for radionuclides with low k_d values.

Step 2: Exposure to Resident Farmer from Well Cuttings

This step addresses drilling a large-diameter well (2 m) and evaluating dose to a resident farmer from contamination brought to the surface in the form of drill cuttings that could be set aside nearby. The drill cuttings are assumed to be spread over the ground surface and the residence built on top of the drill cuttings. In this case, the residence is not assumed to have a basement. Site-specific information should inform the types of scenarios that are evaluated and the assumed parameters.

To bound potential well scenarios, the hypothetical well is assumed to have a large diameter of 2 m versus the smaller diameter of typical water supply wells (4, 5, 6, or 8 inches) (CDC 2006). The larger diameter yields a greater volume of contamination brought to the surface and is therefore more conservative compared to the typical 2 to 6 inch well diameter.

This conceptual model has the following features, some of which are indicated in Figure K-7. The well is dug through 2 m of clean cover material, the CZ of 4 m thickness, and an unsaturated zone of 4 m, for a total depth of 10 m. Assuming mixing of all removed soils, the resulting volume is 31.4 m^3 and the Cs-137 contamination for the drill cuttings is 0.4 pCi/g (4 m contaminated divided by 10 m total depth). The exposure occurs when the subsurface radioactivity is distributed on the ground surface, where it can result in exposure to members of the critical group through the various pathways. The area that the cuttings are spread out and the resulting depth will affect the resulting doses from the dose pathways. The exposure pathways include all those designated for the resident farmer.

[13] As an example, if the RESRAD default erosion rate is changed from 0.001 m/y to a value of 0.01 m/y, the results reflect that at a future date, the erosion of the cover decreases the effectiveness of isolation. With this erosion, the maximum dose occurs after 200 years. The resulting calculated dose is 0.0236 mrem/y per pCi/g, with ground contributing 71 percent and the food pathways the remainder.

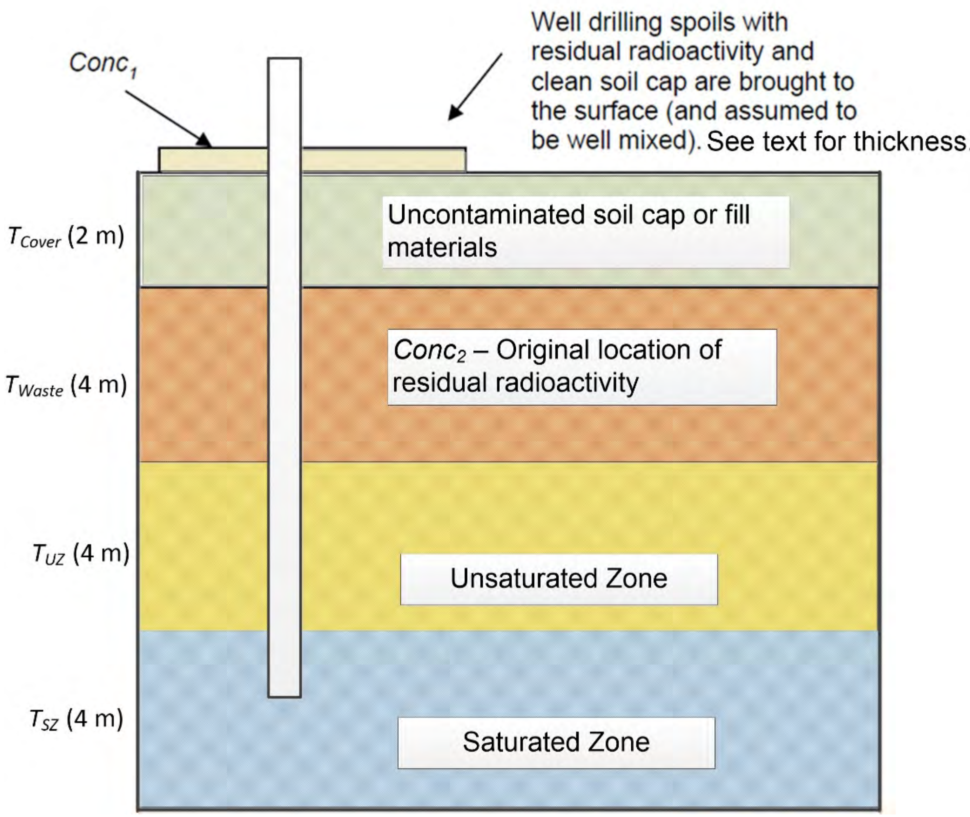

Figure K-7 Conceptual Model for Well Drilling

Source: Modified from NRC 2020c

How large an area the excavated soil is spread out and the thickness of contamination affect the resulting doses from the dose pathways. A sensitivity/uncertainty analysis was conducted to examine the resulting total dose for varying contaminated soil depths, ranging from 15 cm to 50 cm. For conservatism, the exposure pathways considered include all those designated for the resident farmer.[14] Table K-7 shows that as the depth increases, doses also increase slightly though not significantly. For conservatism, a 50 cm depth is assumed.

Table K-7 Sensitivity Analysis Considering Depth of Surface Contamination[a]

Garden Area (m^2)	Spreading Depth	Dose (mrem/year, all pathways)
210	15 cm	0.63
105	30 cm	0.68
63	50 cm	0.70

[a] Except as noted above and in Table K-5, RESRAD-ONSITE parameters were set to default for comparison purposes.

Because the well could be dug before the house was built, it is assumed that the house was also built on top of the cuttings. These assumptions will yield a conservative assessment.

14 For simplicity in illustrating this example, a minimum garden size necessary to support the food pathways is not considered.

The scenario was evaluated using RESRAD-ONSITE with the conservative assumptions described. The resulting dose contributions by pathway were calculated as shown in Table K-8.

Table K-8 RESRAD-ONSITE Pathway Doses for Resident Farmer from Distributed Well Cuttings

Pathway	Effective Dose (mrem/y per pCi/g in CZ)
Direct ground exposure	0.531
Inhalation	8.31E-08
Vegetable ingestion	0.0576
Meat ingestion	0.0419
Milk ingestion	0.0691
Soil ingestion	1.72E-05
Total	0.70

K.2.3 Scenario: Resident Farmer with Intrusions

The residential farmer scenario assumes that someone resides in a house with a basement that penetrates the CZ. During basement excavation, removed contaminated soils are mixed with uncontaminated soils and redistributed on the surrounding ground surface. The resident consumes food grown on the site. This scenario assumes that the hypothetical future resident farmer will excavate a volume of 600 m^3 in building a foundation for a house. The top 2 m of this excavated volume are assumed to be cover material, while the bottom 1 m is considered as contaminated waste (see Figure K-8).

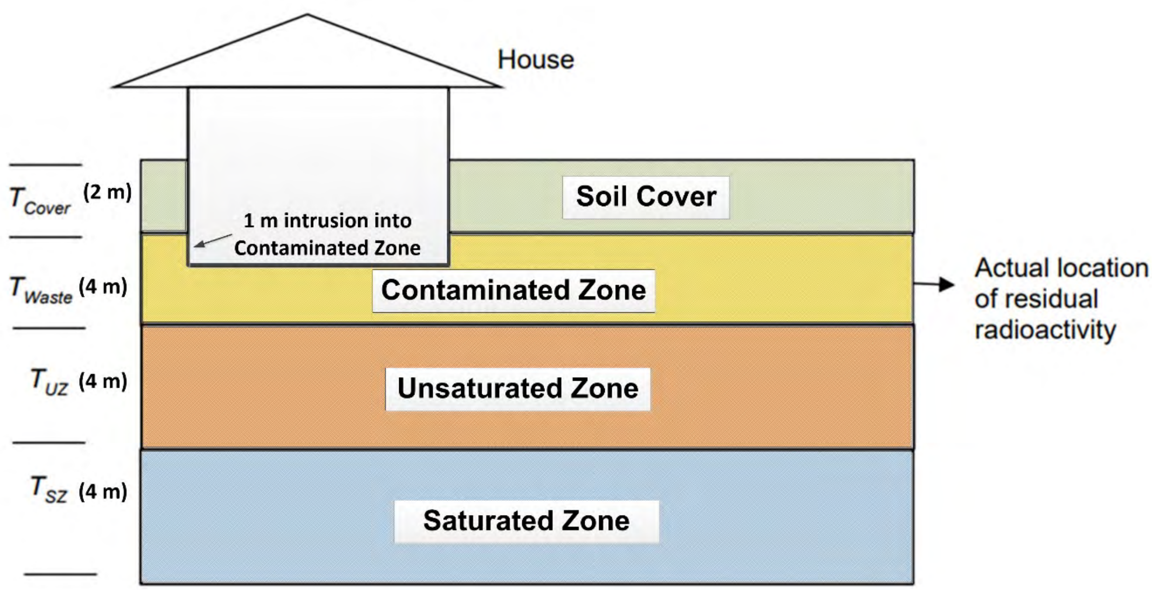

Figure K-8 Conceptual Model for Basement Excavation Intrusion

Source: Modified from NRC 2020c

Figure K-8 shows a conceptual model of the scenario described above, of human disturbance into buried residual radioactivity with a house basement being excavated from a radioactive waste burial pit or an area with elevated residual radioactivity that is located at depth. For this case, the house dimensions are 10 m × 20 m (200 m^2). The depth of the basement is 3 m with 1 m intrusion into the burial pit. The CZ is 4 m deep.

As indicated above, determination of exposures and a DCGL for the resident farmer with intrusion by a basement requires two steps:

(1) Step 1: Determine the direct dose component from exposure inside a house with a basement penetrating into the CZ, considering time spent in the basement and main level.

(2) Step 2: Evaluate the doses resulting from dispersing the basement excavated soils around the home, including food pathways (i.e., resident farmer).

Results of the dose calculations for the exposure scenarios described above are then used for deriving the applicable DCGL for the subsurface Cs-137 contaminated soils.

Step 1: Exposure to a Resident Inside House (Basement and Main Level)

The scenario evaluates the direct dose component to a resident inside a house with a basement extending into the CZ. A 10 m × 20 m house is constructed with the basement projecting 1 m into the CZ. Sources of exposure include the contaminated soil in the CZ as well as the soils removed during basement excavation, mixed and dispersed around the surface area. Dose calculations include time spent in the basement as well as on the main level. The RESRAD and DandD codes do not model an exposure for intrusion into subsurface soils (e.g., a basement constructed within a subsurface CZ). Doses are calculated using MicroShield with the effective dose conversion factors from Federal Guidance Report No. 12.[15] The assumed soil composition, given in Table K-9, is typical of silty soil (ICRU 1994) containing 30 percent water and 20 percent air by volume, with an assumed soil density of $1.6{\times}10^3$ kg m^{-3}. This is soil composition is the same as that used in EPA Federal Guidance Report No. 15, "External Exposure to Radionuclides in Air, Water, and Soil," issued June 2018 (EPA 2018).

Table K-9 Soil Composition

Element	Mass Fraction
H	0.021
C	0.016
O	0.577
Al	0.050
Si	0.271
K	0.013
Ca	0.041
Fe	0.011
Total	1.000

The DandD code has a default indoor occupancy time (0.657 or 240 days). For this case, it is assumed that time is spent equally in the basement and main level. This assumption is subjective but considered reasonable for this example and the resident farmer scenario. The RESRAD and DandD codes do not model a basement constructed within a subsurface CZ. Therefore, the MicroShield code has been used for calculating the direct exposure dose

[15] Federal Guidance Report No. 12 is consistent with dose calculations in 10 CFR Part 20, "Standards for Protection against Radiation"; recent developments by the International Commission on Radiological Protection were not considered for this case study.

component. Table K-10 gives the assumptions as used for this modeling, and Table K-11 presents the results.

Table K-10 Modeling Assumptions for Direct Exposure Inside House

Parameter[a]	Value
Basement intrusion into CZ (m)	1
CZ under basement thickness (m)	3
Initial concentration (pCi/g)	1
Indoor occupancy • Basement occupancy factor • Main level occupancy factor	5,760 hours 0.50 0.50
Receptor location	1 m height at center of each level
House dimensions	10 × 20 meters
Excavated area	600 m^3
House • Basement sidewalls • Foundation slab	3.8 cm concrete 8.9 cm concrete

[a] Except as noted in Table K-5, RESRAD-ONSITE parameters were set to default for convenience.

Table K-11 MicroShield Effective Dose Calculations for 1 pCi/g Cs-137 Subsurface Contaminated

Source/Location	Effective Dose Rate (mrem/h)	Exposure Time (hours/year)	Effective Dose (mrem/y)
CZ/Sidewalls in basement	4.49E-05	2,880	0.517
CZ/Foundation in basement	6.32E-07	2,880	0.182
CZ/Sidewalls on main level	2.33E-07	2,880	0.268
CZ/Foundation on main level	5.87E-07	2,880	0.169
Total			1.14

Step 2: Exposure Pathways from Relocating Excavated Basement Soils

This evaluation was performed with the RESRAD-ONSITE code. The scenario assumes that a volume of contaminated soils from excavation of the house basement (600 m^3) was brought to the surface and spread out over an area adjacent to the house. For this simulation, the unmixed concentration is 1 pCi/g; with mixing at the surface, the initial concentration is 0.333 pCi/g. In addition to the parameters assigned in Table K-5, Table K-12 lists other important parameters assigned in this portion of the case study.

Table K-12 Certain RESRAD-ONSITE Input Parameters for Resident Farmer with Intrusion

Parameter[a]	Second Simulation (Basement Excavation)
Cover or cap (m)	0
Mixed and dispersed soil concentration (pCi/g)	0.333
Outdoor time fraction	0.11
Shielding factor for external (outdoors) gamma radiation[b]	1.0

[a] Except as noted in Table K-5, RESRAD-ONSITE parameters were set to default for convenience.

[b] All inside the house exposure for direct dose calculations performed using MicroShield, evaluated in Step 1, above.

How large an area the excavated soil is spread out and the thickness of contamination affect the resulting doses from the dose pathways. A sensitivity/uncertainty analysis was conducted to examine the resulting total dose for varying contaminated soil depths, ranging from 15 cm to 200 cm. For conservatism, the exposure pathways considered include all those designated for the resident farmer. A depth greater than 50 cm would result in a size considered incapable of supporting an otherwise conservative garden/farming area. Table K-13 shows the resulting total effective dose calculations. As illustrated, the calculated dose increases as the depth increases up to 100 cm depth, then decreases for the 200 cm depth. This decrease is a result of a lower direct dose contribution, caused by the decrease in the effective surface area.

For this example, the dose calculated for the 100 cm depth (0.329 mrem) is used in the DCGL determination. Table K-14 shows the resulting RESRAD-ONSITE pathway dose calculations.

Table K-13 Sensitivity Analysis Considering Depth of Surface Contamination[a]

Garden Area (m^2)	Spreading Depth	Dose (mrem/year, all pathways)
4,000	15 cm	0.164
2,000	30 cm	0.204
1,200	50 cm	0.243
600	100 cm	0.329
300	200 cm	0.254

[a] Except as noted above and in Table K-1, RESRAD-ONSITE parameters were set to default for comparison purposes.

Table K-14 RESRAD-ONSITE Pathway Doses for Resident Farmer with Intrusion

Pathway	Effective Dose (mrem/year)
Direct ground exposure (outside)	0.101
Inhalation	2.59E-08
Vegetable ingestion	0.0864
Meat ingestion	0.0501
Milk ingestion	0.0915
Soil ingestion	1.95E-05
Total	0.329

K.2.4 Third Scenario: Exposure from Well Cuttings to the Well Driller

This third simulation involves a drilling scenario (like the exposure of the resident farmer) and evaluates dose to a hypothetical individual installing a well as a result of contamination brought to the surface in the form of drill cuttings that could be set aside near the well. Like the resident farmer scenario, this scenario assumes a large-diameter well (2 m), which would yield results more conservative than those from smaller diameter wells due to the longer drilling times and the larger volume of cuttings.[16]

Drill cuttings are produced as an advancing drill bit breaks up the rock and soil. The cuttings are usually carried back up the well bore to the surface by drilling fluid circulating up from the drill bit. Figure K-9 illustrates the flow of drilling fluid down the inner shaft to the grinding head and then, when mixed with cuttings, forced to the surface. Although water is the primary constituent of water well drilling fluids, air is also applied in some rotary drilling techniques. This review conservatively considers that air is applied during all drilling time, creating a submersion and inhalation dose.

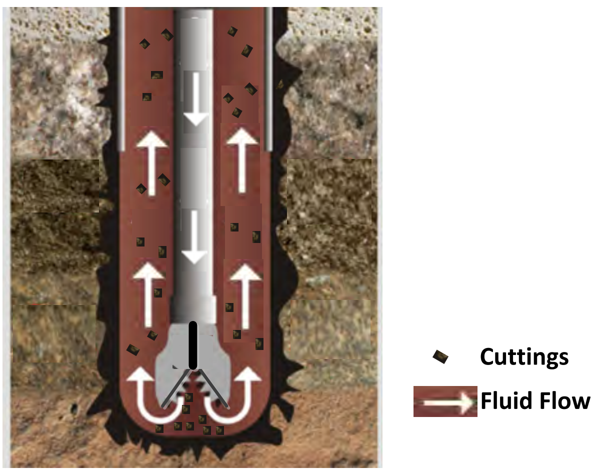

Figure K-9 Fluid and Cuttings Flow

For the residential well sizes, the driller may opt to discharge the cuttings and fluids nearby but away from the wellhead by passing them through a polyvinyl chloride (PVC) pipe as shown in Figure K-10(a), or by simply permitting the cuttings and fluids to discharge at the well head, as shown in Figure K-10(b). Figure K-10(b) illustrates how cuttings can pile up at the wellhead at the discretion of the driller; the illustrated pile is for a well depth of about 120 feet (40 m).

The exposures accounts for these characteristics of well cuttings and drilling fluids. Both the cuttings and drilling fluids carry the radionuclides of concern above ground. During drilling operations, the driller will be continuously at the side of the cuttings as shown in Figure K-10(b).

[16] Site-specific information should be used to support assumed well diameters. For the purposes of this exercise, the Centers for Disease Control and Prevention (CDC) suggests that the depth of bored wells range from 0–100 feet (0–30 m) and have a diameter of 2–30 inches (5–75 cm); however, commercial augers are available in the 2 m diameter range (CDC 2006).

Figure K-10 Illustrations of Well Cuttings and Fluid Discharges

Source: (a) Lee 2022, (b) Bailey Line Road 2022

The assumptions about the depth and surface area of contamination significantly impact the resulting dose for the acute or chronic well intruder scenarios. As for the resident farmer, the well will be cut through a 2 m clean cover, a 4 m CZ, and a 4 m unsaturated zone, as illustrated in Figure K-7. The main component of the acute well intruder scenario is the assumption that over the duration of the drilling, the noncontaminated waste residuals from the clean cover would be the first material excavated, followed with contaminated material and then increasing thicknesses of clean material from the unsaturated zone. Three pathways are considered—external gamma, soil ingestion, and inhalation. This simulation requires two steps:

(1) Step 1: Calculate external gamma doses.
(2) Step 2: Calculate doses from inhalation, ingestion.

Step 1: Calculation of External Gamma Doses

For simplicity and a bounding dose assessment, it is assumed that the well driller stands on an infinite volume of the extracted and mixed soils for the duration of the drilling and well casing and configuration time. A well such as the one considered in this case study could require about a week to complete drilling, capping, and hookup. This scenario conservatively assumed that a single individual supports the drilling, capping, and hookup, with a total exposure time of 5 days (40 hours).

Table K-15 shows the assumptions and resulting calculated dose. The infinite soil dose conversion factor is from EPA Federal Guidance Report No. 15.

Table K-15 Exposure Assumptions and Dose Calculation for Well Drilling

Mixed Soil Cs-137 Concentration (pCi/g)	Soil Density (g/cm^3)	Infinite Soil Dose Conversion Factor (mrem/h per pCi/cm^3)	Exposure Time (hours)	Dose (mrem)
0.4	1.6	2.57E-04	40	6.6E-03

Step 2: Calculation of Doses from Inhalation, Ingestion, and Submersion

The effective dose equivalent (EDE), *H*, to an individual from inhalation and ingestion of a radioactive material is given by Equation K-6:

$$H = DCF \times I \qquad \text{(Eq. K-6)}$$

where:

I = intake of an individual by inhalation or ingestion (µCi)

DCF = dose conversion factor for the 50-year committed EDE from inhalation or ingestion (mrem/µCi) (EPA 1988)

The EDE (mrem) to an individual from submersion in airborne radioactive material is given by Equation K-7:

$$H = DCF \times C \times t \qquad \text{(Eq. K-7)}$$

where:

t = time of an individual's exposure (h)

C = average concentration of the airborne material (µCi/m^3) over the time, t

DCF = dose conversion factor for air submersion (mrem-m^3/µCi-h) (see EPA 2018); a skin dose component was not applied as workers are assumed to wear protective clothing

Table K-16 presents the dose conversion factors.

Table K-16 Dose Coefficients for Cs-137 (+ Ba-137m)

Air Submersion[a] (mrem-m^3/µCi-h)	Ingestion[b] (mrem/µCi)	Inhalation[c] (mrem/µCi)
0.36	50	31.9

[a] EPA 2018, Table 4-6
[b] EPA 1988, Table 2.2, for ingestion
[c] EPA 1988, Table 2.1, for inhalation

The following values were applied for these calculations:

- The DandD soil ingestion rate was 18.26 g/year or 0.05 g/day. This was applied for a 5-day period (NRC 1999).
- The DandD breathing rate was 11,690 m^3 per year or 1.33 m^3 per hour (NRC 1999).
- During drilling, an airborne level at the Occupational Safety and Health Administration (OSHA) permissible exposure limits of 15 mg/m^3 is assumed (OSHA 2022).

Table K-17 presents the results of calculated doses to the well driller. In summary, direct radiation is the dominant exposure pathway; inhalation, ingestion and submersion are relatively minor contributors.

Table K-17 Pathway Doses for 2 m Diameter Well

Gamma Exposure (mrem)	Ingestion Dose (mrem)	Inhalation Dose (mrem)	Submersion Dose (mrem)	Total Dose (mrem)
6.6E-03	5E-06	1E-05	9E-08	7E-03

K.2.5 Exposure and Derived Concentration Guideline Level Summary

Table K-18 summarizes each scenario, giving the exposure rates for the initial 1 pCi/g concentrations in the CZ and the related DCGLs. For the evaluated scenarios, the CZ concentration DCGL for a 25 mrem annual dose that is most restrictive is for the resident farmer with a house/basement into the CZ. The DCGL for the subsurface soil contaminated with Cs-137 is 17 pCi/g.

Table K-18 Doses and Resulting DCGLs

Scenario	Description	Dose (mrem/year per pCi/g in CZ)	CZ DCGL (pCi/g)
1, Resident farmer with well	Exposure from subsurface (no intrusion)	4.33×10^{-13}	36
	Exposure from distributed well cuttings	0.70	
2, Resident farmer with intrusion	Exposure inside house with basement into CZ	1.14	17
	Exposure from distributed excavated soil	0.329	
	Indoors exposure, house occupancy	1.31 mrem/year	
3, Well Driller	Exposure during drilling, capping, and hookup	0.007 mrem	3,600

K.2.6 Evaluation of Existing Survey Data by GIS and Geostatistical Tools

The hypothetical site is 100 m × 60 m with a strip of subsurface contamination running from the southwest to the northeast, as shown in Figure K-11. Any proposed building footprint of 10 m × 20 m is assumed to located within the subsurface contaminated area. As the house could be placed anywhere in any orientation, the entire CZ footprint must be considered.

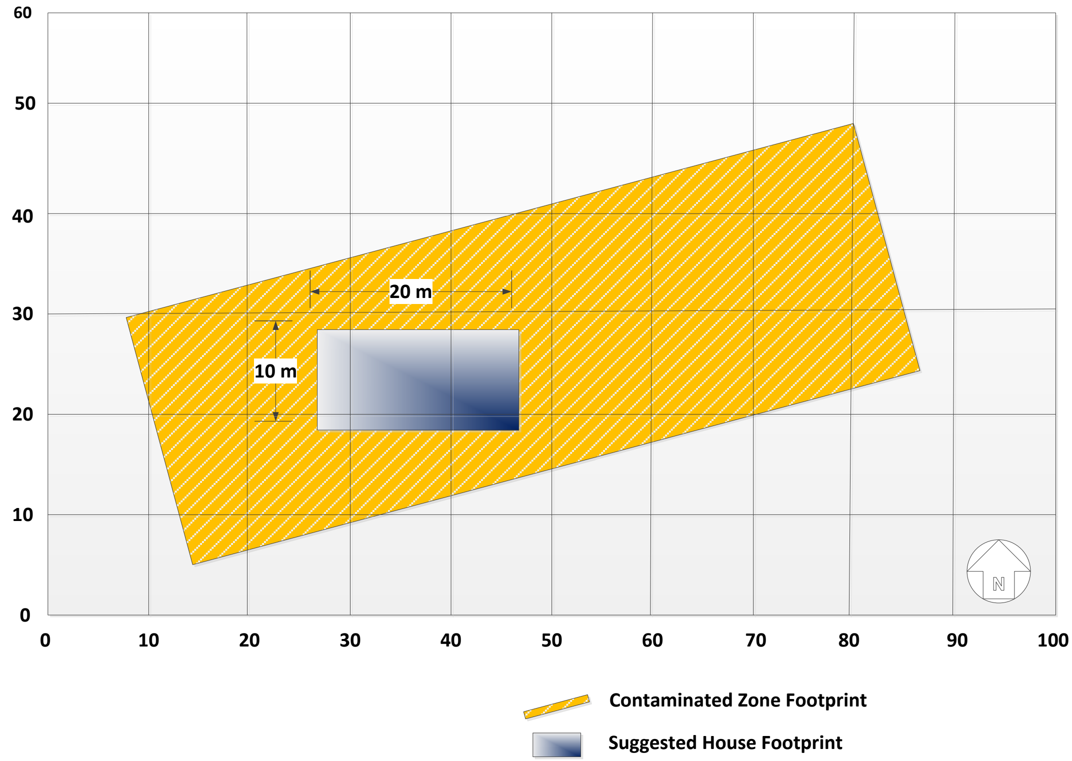

Figure K-11 Hypothetical Site Layout

As stated in Section 2.5 of the main report, in 2012, the NRC published NUREG/CR-7021, which describes SADA. SADA incorporates use of an evolving contamination of concern map (Stewart et al. 2009). NUREG/CR-7021 provides a geospatial modeling decision framework for conducting a subsurface vadose zone compliance survey and analysis. The framework proposes a method to extend the MARSSIM guidance into the vadose zone, with possible applications to ground water (Stewart et al. 2009). As indicated in Section 6 of the main report, geostatistical tools can be used for radiological characterization of nuclear facilities during decommissioning and for contaminated sites under remediation, including sampling optimization, exploratory data analysis, and two- and three-dimensional maps of activity levels. This case study applied these tools.

K.2.6.1 Characterization Sampling Campaign

For this case study, the historical site assessment did not report the exact surface coordinates of the CZ, so for the purposes of this example, the area is gridded into 10 m square grids and a core sample was collected at each vertex. In keeping with the modeling, each core sample for this hypothetical campaign would be 1 m in length, beginning with the second meter of the cover, then each of the 4 m in the CZ, and the first meter below the CZ, for a total of six samples per core.

Overall, this effort resulted in 180 initial characterization samples within the CZ, ranging from 0.05 to 35 pCi/g and a mean of 9.1 pCi/g. The results were plotted with SADA, and a visual review confirms that the CZ ran from the southwest to the northeast across the site, as shown in Figures K-12 and K-13. Figure K-12 depicts a three-dimensional posting of all the results of the CZ core samples, while Figure K-13 illustrates the results for the first meter of the CZ.

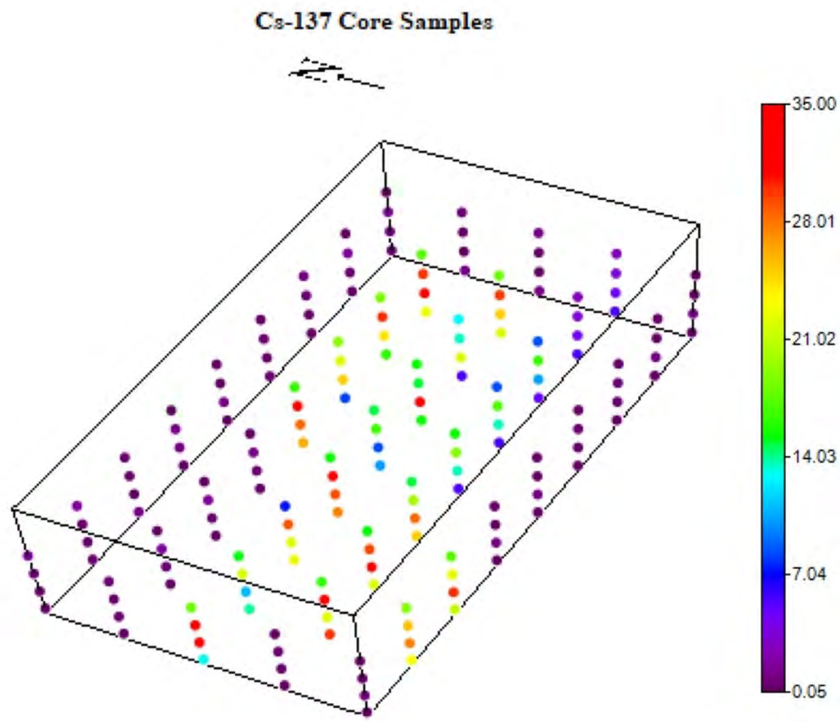

Figure K-12 Three-Dimensional Results for All Samples

Source: SADA graphic

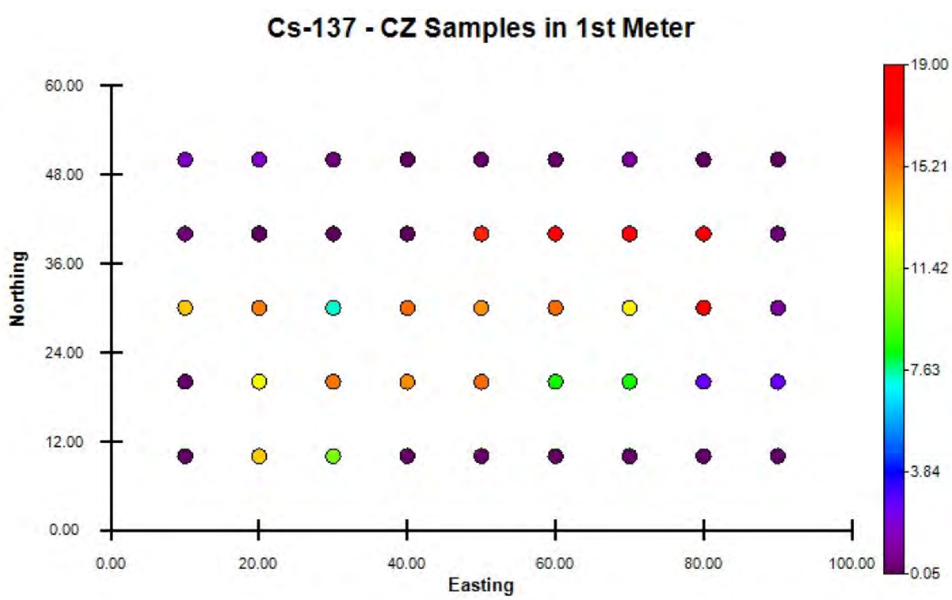

Figure K-13 Posting Plot Results for CZ First Meter Samples

Source: SADA graphic

K.2.6.2 Examination of First Meter of the Contaminated Zone

Results shown in Figure K-13 of samples from the first meter of the CZ are greater than the 16 pCi/g DCGL for the resident farmer intrusion scenario. Figure K-14 shows the orientation of three potential house footprints on the site covering areas with the highest results.

As this visual review indicates that the three areas qualify as potential elevated areas, additional survey is warranted. For the purposes of this case study, the licensee and the regulatory agency agreed to the collection of additional samples within each footprint in the first meter of the CZ, indicated in Figure K-14 with "⊗". There was hope that additional sampling results with overall averaging might confirm that the DCGL was not exceeded. Actual placement of the locations provided a total of five results in Footprint A, six results in Footprint B, and six results in Footprint C.

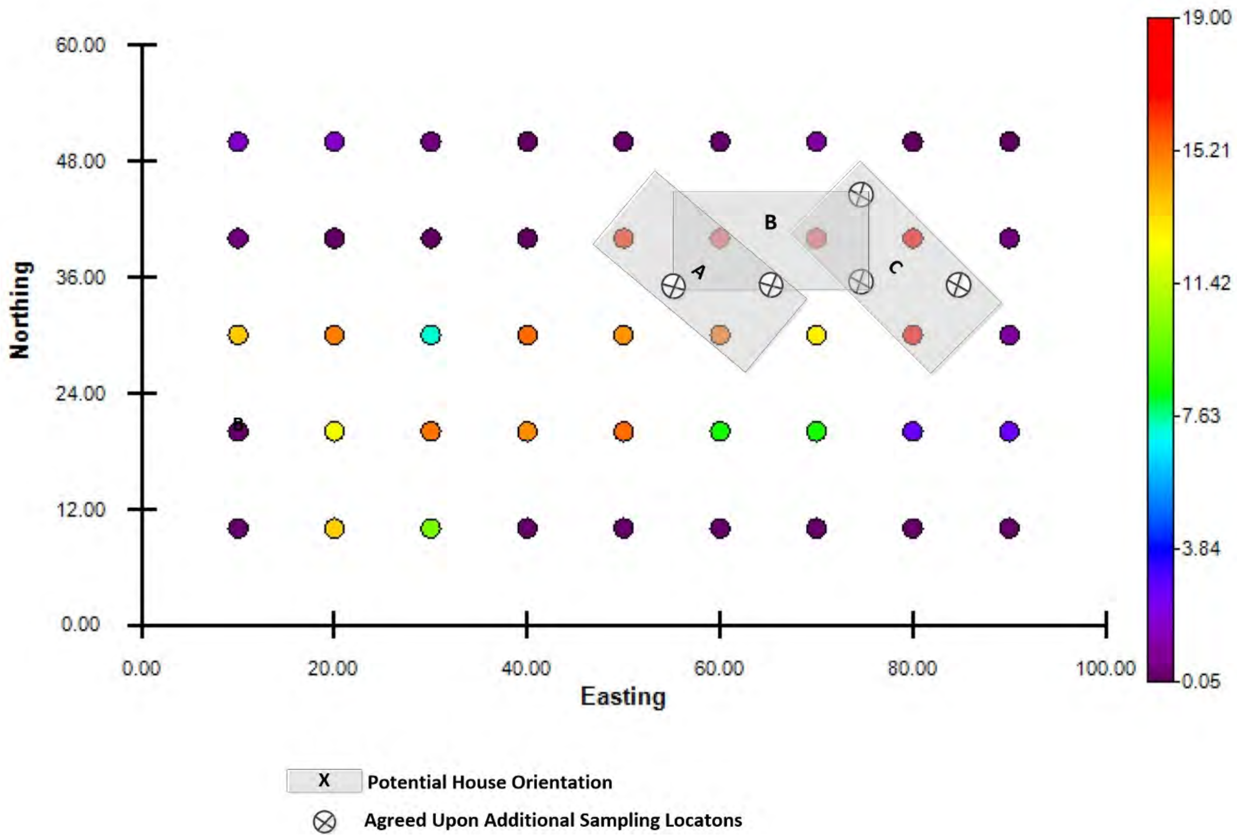

Figure K-14 Grid Plot of First Meter CZ Characterization Results with Potential House Orientations

Source: SADA graphic with housing overlay

The additional samples were collected, and the results are summarized in Table K-19. The results and standard deviations of the three footprints are remarkably similar; the results indicate subsurface levels at or above the DCGL. Figure K-15 presents a SADA grid plot of the first meter final CZ results with the potential house orientations.

Table K-19 Final Characterization Sample Results within Each Footprint

Footprint	Easting	Northing	Value (pCi/g)	Average (pCi/g)	σ (pCi/g)
A	50	40	16.4	16.2	1.8
	60	30	15.4		
	60	40	19.0		
	55	35	16.3		
	65	35	14.0		
B	55	35	16.3	16.2	2.3
	60	40	19.0		
	65	35	14.0		
	70	40	18.5		
	75	35	16.2		
	75	45	13.4		
C	70	40	18.5	16.1	2.0
	75	35	16.2		
	75	45	13.4		
	80	40	17.3		
	85	35	15.2		

The means for each house footprint were above the DCGL.

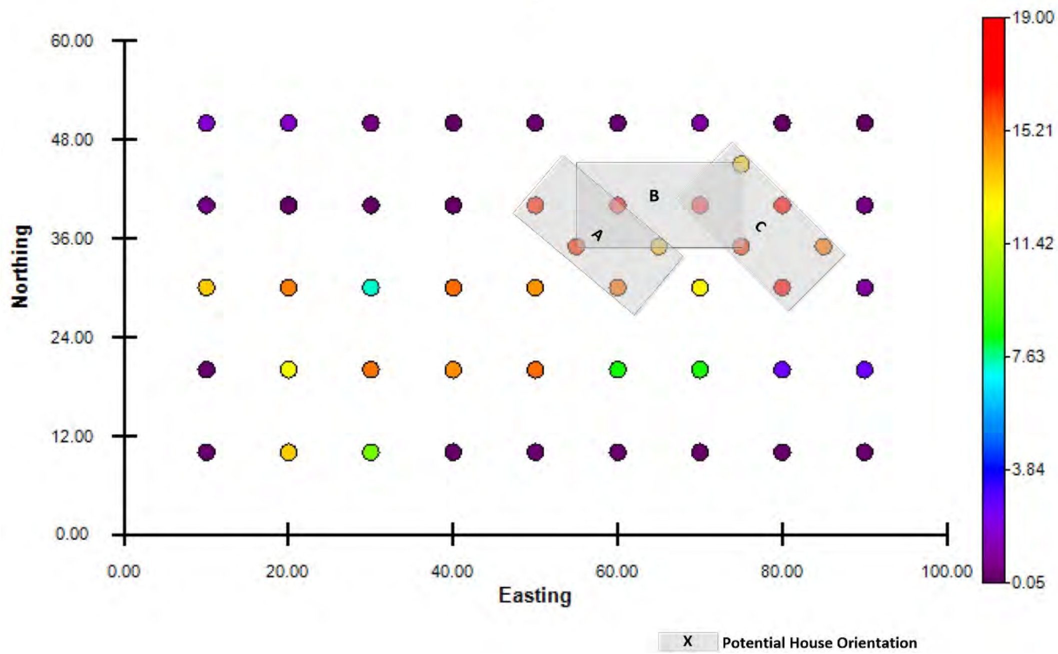

Figure K-15 Grid Plot of First Meter Final CZ Results with Potential House Orientations

Source: SADA graphic with housing overlay

K.2.6.3 Examination of the Contaminated Zone Core Averages

Figure K-16 provides a grid plot of the CZ core averages, showing regions exceeding the DCGL of 13.2 pCi/g.

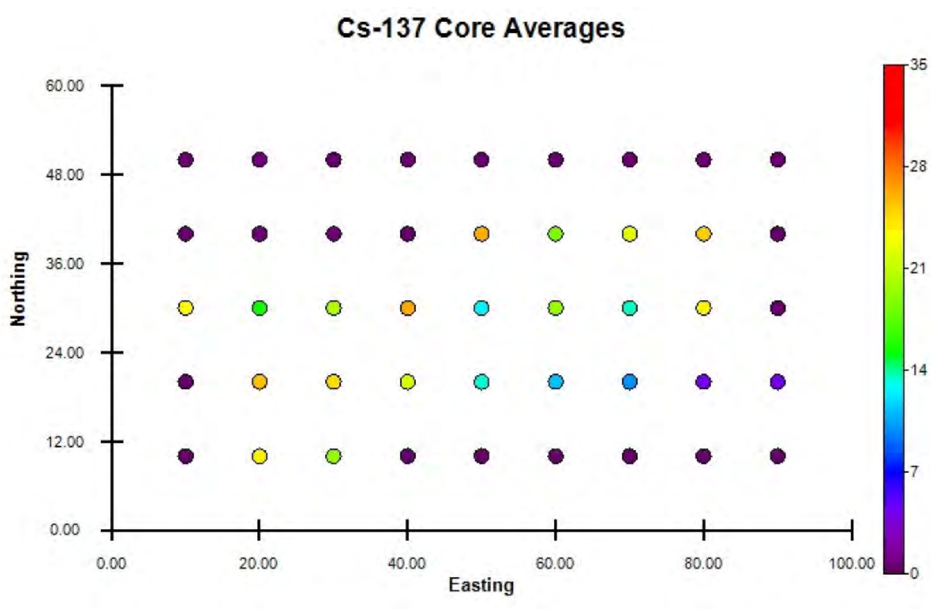

Figure K-16 Grid Plot of CZ Core Average Results

Source: SADA graphic with housing overlay

K.2.6.4 Estimating Concentration between Data Points

The SADA software offers several methods to estimate concentration in areas not directly sampled, one of them being *Natural Neighbor*. In *Natural Neighbor*, not only the nearest neighbor result is allowed to influence the estimation. When data points are distributed in space, they inherently represent a certain defined area around them. Sample points in sparsely sampled regions represent a larger region than those in more densely sampled areas. These regions are named the *area of influence*, and SADA draws simple geometries that bound them (Stewart et al. 2009).

When using SADA's *Natural Neighbor*, the data areas of influence are calculated first and then the area of influence for the point being estimated is overlaid. This calculation creates regions of overlapping areas of influence. For any sample point, the fraction of the overlap becomes the weight assigned to that sample point. This is illustrated in Figure K-17 and is formally written as in Equation K-8:

$$u_0 = \sum_{i=1}^{N} \frac{a_i}{A} u_i \quad \text{(Eq. K-8)}$$

where:

N = the number of intersecting areas of influence
A = the area of the area of influence for u_0
a_i = the area of overlap between u_0 and u_i (Stewart et al. 2009)

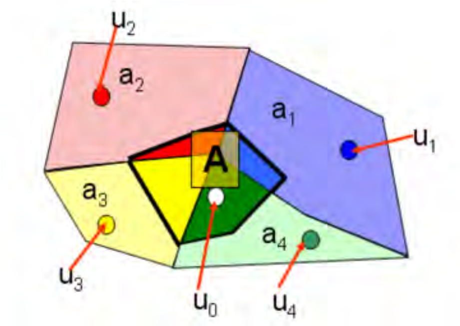

Figure K-17 Natural Neighbor Concept

Source: Stewart et al. 2009, p. 278

Applying the *Natural Neighbor* concept to this case study for the first meter of contamination produces the visual shown in Figure K-18. This figure generally identifies the regions of the identified subsurface contamination that require additional evaluation for remediation.

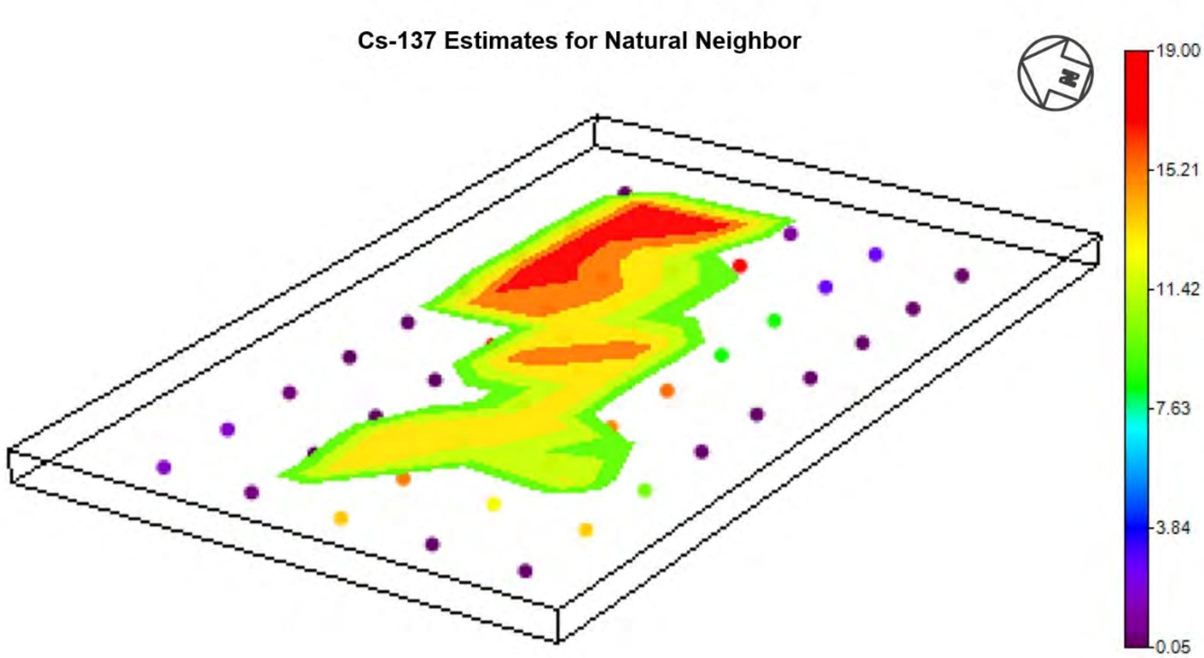

Figure K-18 Natural Neighbor Analysis for First Meter of CZ

Source: SADA graphic

Figure K-19 provides a graded view of average core results; the location where the highest value is expected is shown in red.

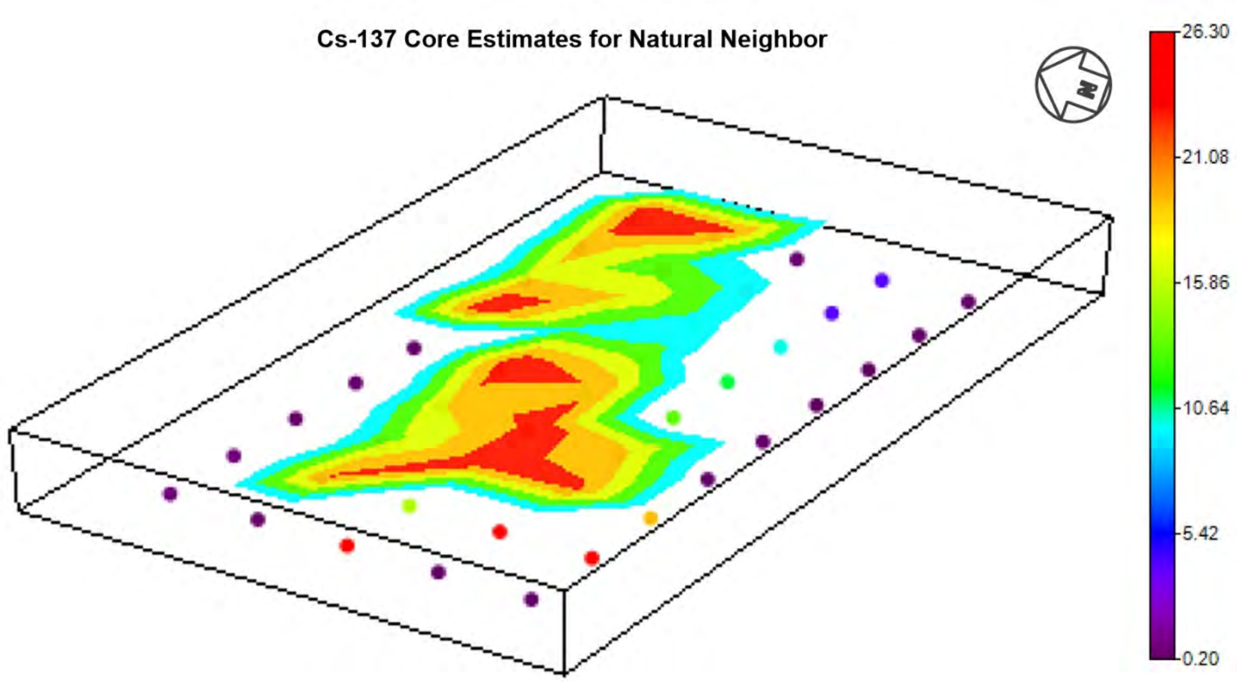

Figure K-19 Natural Neighbor Analysis for Cores (4 meters) of CZ

Source: SADA graphic

Comparison of the analysis in Figures K-18 and K-19 provides further evidence that regions of the identified subsurface contamination require additional evaluation for demonstrating compliance with the DCGL.

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APPENDIX L

CASE STUDIES FOR SADA AND VSP

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Figures

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L.1 Introduction

Generally, the purpose of a case study approach is to allow in-depth, multifaceted explorations of complex issues in their real-life settings. A case study related to surface contamination would establish the parameters for the survey design, namely the contaminant of concern, action level, the site to be studied, and the decision rule to be used. Surveys would be performed as designed and analyzed using the decision rules as established. In essence, final status surveys would be done for surface (top 15 centimeters) survey units containing cesium-137, uranium (U)-238, and thorium (Th)-232. The approach in NUREG-1575, Revision 1, “Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM),” issued August 2000 (NRC 2000), would be appropriate for the purpose.

For subsurface studies, the situation is considerably more complex. The parameters for sample design have not been established and decision rules have not been formalized. Existing data sets are not readily available and are largely the result of historical or judgmental survey designs. An opportunity study is executed in the early stages of a project. The scope of the study is an examination of a project idea. This white paper identified examples of possible approaches, with Pacific Northwest National Laboratory’s Visual Sample Plan (VSP) and Oak Ridge National Laboratory/University of Tennessee Spatial Analysis and Decision Assistance (SADA) as two of the best alternatives for building approaches for designing and evaluating subsurface survey units.

To illustrate the types of analyses that can be done using VSP and SADA software, this appendix section considers two instances of data obtained at a site with elevated U-238 and Th-232. These data were obtained using bismuth (Bi)-214 and actinium (Ac)-228 measurements of soil cores taken at the site. Each foot of these soil cores was analyzed, and samples were taken from the depth layer that yielded the highest counts per minute values. The results generally showed elevated concentrations in samples 3–6 feet in depth. These 3–6-foot data were used as input to both VSP and SADA as if they represented a single layer of contamination. After segregating all samples within the 3–6 foot depth layer, the Easting, Northing, radionuclide, and concentration values for each were used as the primary input values. Samples taken at the same location but at different depths within this range were both included in the analyses.

Furthermore, while elevation data are present in the original data, neither SADA nor VSP use surface elevation in their calculations. In particular, it was determined the z value of a data point is not used in VSP’s geostatistical calculations. Elevation is not required for import into either program for calculation purposes, although it was imported into SADA in this study. For correct processing of the samples in three-dimensional (3D) space, the user must specify the depth, or z location, of a sample.

The objective here is to see how far the analysis of the same data can be carried in each program, and how the results compare. At this stage of development, it was found that neither software tool is capable of designing a complete Bayesian Ellipgrid primary sample plan nor a Markov-Bayes secondary sample plan. However, simple univariate statistics and posting plots were obtained and compared, and they yielded consistent results. Each of these programs does contain core capabilities that might be developed into a useful tool for subsurface surveys. The advantages and disadvantages of each are noted where appropriate.

L.2 Preparing the Data

Project data can be compiled into many formats and be arranged in different ways. The first step is to prepare the data so that it can be imported into the software program being used. The data set for this case study in its original form could not be imported to SADA or VSP and first required restructuring. These software programs require a similar structuring of the data for import, although with some technical differences. Considerable effort was required to arrange appropriate input data files that were consistent with both programs and would result in survey data locations and contaminant data that were the same for both.

L.2.1 SADA Import

SADA allows users to import sampled data in two formats, either through a Comma Separated Value (.csv) file, or via a Microsoft Access database. The .csv approach was used for this case study.

When importing using either format, SADA can use the following information when assigned to individual columns:

- easting
- northing
- depth
- sampled values
- name
- CAS numbers
- detection qualifiers
- date
- media
- sample ID

Of these, only the fields Easting, Northing, and Sampled Values are required for a successful import; however, to perform 3D kriging on multiple analytes as in this case study, the Depth and Name fields were also required:

- <u>Easting</u>: X coordinate of sample
- <u>Northing</u>: Y coordinate of sample
- <u>Sampled Values</u>: results of analytical analyses
- <u>Depth</u>: depth of sample below the surface; needs to use the same units as provided for Easting and Northing
- <u>Name</u>: name of contaminant

For SADA to properly process the .csv file, each analytical result must have its own unique row. Samples taken at multiple depths for multiple analytes must repeat descriptive information in each row. In this case study, each location was sampled at several depths for two separate radionuclides, Bi-214 and Ac-218, and the original data set had this information in one row per location with the different samples and analytes in separate columns. This data set also included elevation values describing the relative ground surface elevation from the lowest point of the site. Elevation here is ignored, and instead depth is considered to be from a level ground surface. The original file included depth as a range. As neither SADA nor VSP supports import of a range for depths, for simplicity, the shallowest depth of the sample's depth range (i.e., the first value in the range) was used as the depth value for input. For example, samples taken from 0–1 foot were considered to be 0 feet. Depths were depicted as negative values for the purposes of subsurface consideration from a level ground surface.

Figure L-1 is an excerpt of the data set in its original form, which would not be compatible with SADA requirements.

Note that VSP and SADA assume that the reference or surface elevation is the same at every point, although the elevation column in Figure L-1 shows that this is not actually the case with the original field sampling. Should a user wish to account for variance in surface elevation, the depth values, if provided, would need to be adjusted manually to reflect a depth below a certain elevation.

	A	B	C	D	E	F	G
1	**Sample ID**	**ELEVATIONS**	**Y**	**X**	**Depth**	**LAB Ac-228 (Th-232) (pC/g)**	**LAB Bi-214 (Ra-226) (pC/g)**
2	1	1.48	442.065	234.969	0-1 ft	2.35	2.79
3	5	6.18	399.933	318.034	9-10 ft	0.778	0.444
4	7	6.14	373.365	307.667	0-1 ft	1.29	0.764
5	7	6.14	373.365	307.667	9-10 ft	0.922	0.662
6	8	5.51	352.712	290.079	8 - 9 ft	0.763	0.476
7	8	5.51	352.712	290.079	8 - 9 ft	0.568	0.599
8	8	5.51	352.712	290.079	9 - 10 ft	0.792	0.706
9	9	5.47	349.626	297.501	0 - 1 ft	0.732	0.496
10	9	5.47	349.626	297.501	9 - 10 ft	0.689	0.611
11	10	5.78	330.986	302.07	0 - 1 ft	0.864	0.915
12	10	5.78	330.986	302.07	9 - 10 ft	0.73	0.409
13	11	5.44	366.688	313.156	0 - 1 ft	1.16	1.06
14	11	5.44	366.688	313.156	9 - 10 ft	0.516	0.45
15	12	5.34	376.786	329.157	9 - 10 ft	0.506	0.591

Figure L-1 Original Unformatted Data Set

To prepare it for SADA import, the file was originally reformatted to have four rows for each location to accommodate the different sampling depths and analytes.

Figure L-2 gives an example from SADA's Help documentation, and Figure L-3 provides a portion of the adapted data set to meet SADA import requirements. It should also be noted that, while not a required field, data sets where samples have identical x, y, and z values taken on the same date and time will not be fully imported. Instead, SADA will import only one of the two values. The SADA criterion for which is dropped is not known. For simplicity, samples marked as duplicate were removed from the data set. The values, relative distances between sample locations, and depths are all that are necessary for this example. Imported elevation values were not considered by SADA in its calculations.

	A	B	C	D	E	F	G	H	I	J	K
1	Easting	Northing	Depth	Casnumber	Name	Value	Detected	Media	Date	SampleID	Region
2	27596.25	21900	0	14265851	Ac-225	2	1	SO	9/26/1970	1	1
3	28310.25	21900	0	14265851	Ac-225	1.6	1	SO	9/26/1970	2	1
4	28935	21900	0	14265851	Ac-225	0.9	1	SO	9/26/1970	3	1
5	27685.5	22200	0	14265851	Ac-225	2	1	SO	9/26/1970	4	1
6	28131.75	22200	0	14265851	Ac-225	4.2	1	SO	9/26/1970	5	1
7	29202.75	22500	0	14265851	Ac-225	1.5	1	SO	9/26/1970	6	1
8	27150	23160	0	14265851	Ac-225	1.7	1	SO	9/26/1970	7	1
9	27685.5	22920	0	14265851	Ac-225	3.6	1	SO	9/26/1970	8	1
10	28042.5	23100	0	14265851	Ac-225	4.9	1	SO	9/26/1970	9	1
11	28221	23100	0	14265851	Ac-225	4.2	1	SO	9/26/1970	10	1
12	28667.25	23220	0	14265851	Ac-225	2.9	1	SO	9/26/1970	11	1
13	29113.5	22980	0	14265851	Ac-225	1	1	SO	9/26/1970	12	1
14	27417.75	23580	0	14265851	Ac-225	1.9	1	SO	9/26/1970	13	1
15	27774.75	23640	0	14265851	Ac-225	2.9	1	SO	9/26/1970	14	1
16	28310.25	23400	0	14265851	Ac-225	3.1	1	SO	3/22/1993	15	1
17	28935	23460	0	14265851	Ac-225	0.8	1	SO	3/22/1993	16	1
18	28200	22560	0	14265851	Ac-225	4.8	1	SO	3/22/1993	17	1
19	28700	22500	0	14265851	Ac-225	3.3	1	SO	3/22/1993	18	1
20	27200	22380	0	14265851	Ac-225	2.03	1	SO	3/22/1993	19	1
21	28984	22787	0	14265851	Ac-225	2.6	1	SO	3/22/1993	4	1
22	27350	22750	0	14265851	Ac-225	2.5	1	SO	3/22/1993	3	1
23	27026	22129	0	14265851	Ac-225	1.7	1	SO	3/22/1993	2	1
24	27690	23350	0	14265851	Ac-225	2.6	1	SO	3/22/1993	4	2
25	27500	23270	0	14265851	Ac-225	2.5	1	SO	3/22/1993	44f	2
26	28709	22900	0	14265851	Ac-225	2.7	1	SO	3/22/1993	43	2
27	27650	22500	0	14265851	Ac-225	3.4	1	SO	3/22/1993	33	2
28	28530	22700	0	14265851	Ac-225	3.3	1	SO	3/22/1993	11	2
29	27750	23145	0	14265851	Ac-225	3.2	1	SO	3/22/1993	12	2
30	27596.25	21900	0	7440393	Barium	42.7	1	SO	8/7/1996	13	2
31	28310.25	21900	0	7440393	Barium	35.1	1	SO	8/7/1996	14	2
32	28935	21900	0	7440393	Barium	18.4	1	SO	8/7/1996	15	2
33	27685.5	22200	0	7440393	Barium	43.5	1	SO	8/7/1996	16	2
34	28131.75	22200	0	7440393	Barium	87.9	1	SO	8/7/1996	17	2

Figure L-2 Formatted Data Table for SADA Input from SADA Documentation

Source: Stewart et al. 2009, p. 59

	A	B	C	D	E	F	G	H	I
1	SampleID	Elevation	Northing	Easting	Date	Depth	Name	Value	Media
2	18	3.79	184.968	60.5111	1/1/1999	-6	Ac-228	1.01	SO
3	22	4.1	255.762	531.791	1/1/1999	-4	Ac-228	26.8	SO
4	23	4.2	258.855	506.054	1/1/1999	-5	Ac-228	728	SO
5	26	4.11	273.241	345.176	1/1/1999	-4	Ac-228	1.24	SO
6	27	4.23	164.344	337.597	1/1/1999	-5	Ac-228	0.877	SO
7	32	4.01	285.521	562.54	1/1/1999	-4	Ac-228	75.1	SO
8	33	3.91	305.621	573.984	1/1/1999	-4	Ac-228	98.4	SO
9	34	4.78	350.391	465.271	1/1/1999	-5	Ac-228	1.65	SO
10	39	6.07	377.632	432.645	1/1/1999	-3	Ac-228	1.11	SO
11	52	3.79	169.691	447.711	1/1/1999	-3	Ac-228	1.41	SO
12	54	4.04	106.991	493.239	1/1/1999	-3	Ac-228	2.23	SO
13	55	3.36	10.4635	397.374	1/1/1999	-4	Ac-228	107	SO
14	58	5.67	353.882	478.98	1/1/1999	-5	Ac-228	0.982	SO
15	60	4.11	326.204	544.377	1/1/1999	-4	Ac-228	20.2	SO
16	61	2.18	241.993	727.833	1/1/1999	-3	Ac-228	1.3	SO
17	62	2.27	231.91	746.774	1/1/1999	-4	Ac-228	1.46	SO
18	63	4.2	255.194	642.449	1/1/1999	-3	Ac-228	10.6	SO
19	64	4.22	200.985	579.366	1/1/1999	-4	Ac-228	0.883	SO
20	65	2.84	393.788	179.236	1/1/1999	-4	Ac-228	1.81	SO
21	71	0	457.664	114.023	1/1/1999	-3	Ac-228	1.17	SO
22	73	0.11	409.479	129.305	1/1/1999	-3	Ac-228	0.922	SO

Figure L-3 Formatted Data Set Imported to SADA

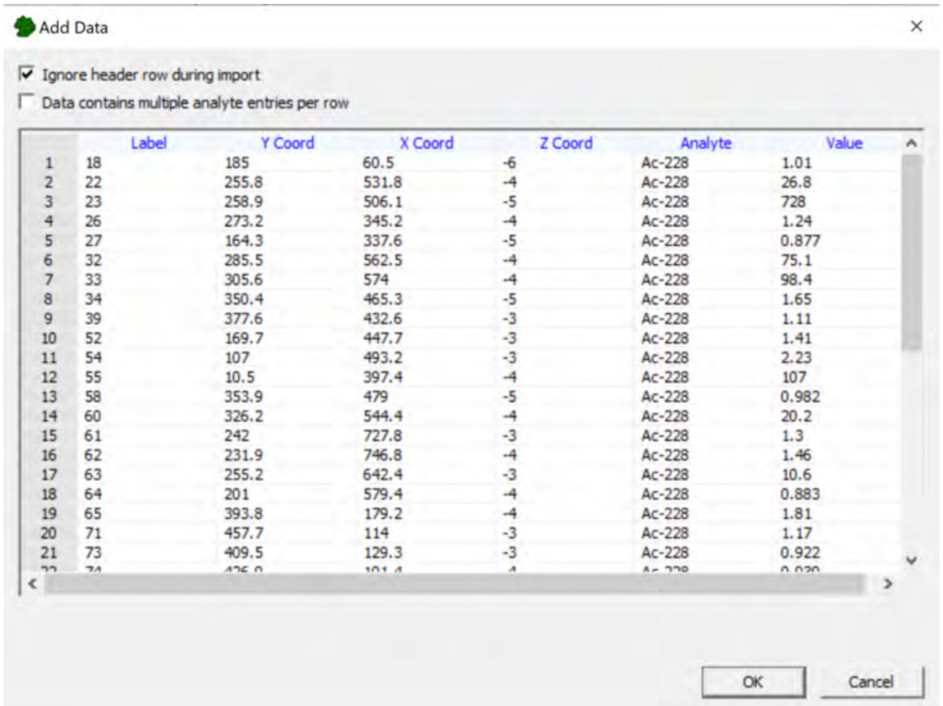
Once the file is properly formatted, selecting the “Import Sampled Data” option from the “Data” tab will open a directory and the user chooses the file containing the sample data. If no errors with the file are found, the “Column Matching” dialogue will open to allow the user to match SADA parameters to the appropriate field in the imported file. For parameters that do not have a match in the imported file, No Match should be selected. If no CAS Number or Detect field is matched, SADA will provide options to automatically fill this information to complete the import. SADA will notify the user of duplicate results and allow the user to proceed, although not all samples will be imported if the user chooses to ignore this issue.

L.2.2 VSP Import

The same data structure used for importing to SADA also functions for import to VSP. However, VSP allows multiple analytes and values to be listed in the same row. Each analyte was listed on a separate row to maintain consistency between programs.

Unlike SADA (described in Section L.2.1), VSP only allows the import of tab-delimited text files. As an alternative, VSP allows users to paste copied data directly from an Excel file. To paste in the data set, the user navigates to “Tools,” then “Analyze Data,” then opens the data import dialogue. The user can then copy the sample data set from their file and select paste in VSP to import the table. Figure L-4 gives an example paste operation. VSP will then ask users to specify what each column represents. Columns with extraneous data can also be set to be ignored during import. Clicking “OK” will finalize the import to VSP. No data errors were identified in the pasted material.

Another difference between the two imports is that VSP provides a prelabeled z coordinate rather than a depth as SADA does. These two are the same by definition, although VSP does not currently use this information as 3D data. Instead, the data are essentially compressed to two dimensional data (2D) as is clarified in following sections. In the data pasted to VSP, this is labeled as "Depth."



	Label	Y Coord	X Coord	Z Coord	Analyte	Value
1	18	185	60.5	-6	Ac-228	1.01
2	22	255.8	531.8	-4	Ac-228	26.8
3	23	258.9	506.1	-5	Ac-228	728
4	26	273.2	345.2	-4	Ac-228	1.24
5	27	164.3	337.6	-5	Ac-228	0.877
6	32	285.5	562.5	-4	Ac-228	75.1
7	33	305.6	574	-4	Ac-228	98.4
8	34	350.4	465.3	-5	Ac-228	1.65
9	39	377.6	432.6	-3	Ac-228	1.11
10	52	169.7	447.7	-3	Ac-228	1.41
11	54	107	493.2	-3	Ac-228	2.23
12	55	10.5	397.4	-4	Ac-228	107
13	58	353.9	479	-5	Ac-228	0.982
14	60	326.2	544.4	-4	Ac-228	20.2
15	61	242	727.8	-3	Ac-228	1.3
16	62	231.9	746.8	-4	Ac-228	1.46
17	63	255.2	642.4	-3	Ac-228	10.6
18	64	201	579.4	-4	Ac-228	0.883
19	65	393.8	179.2	-4	Ac-228	1.81
20	71	457.7	114	-3	Ac-228	1.17
21	73	409.5	129.3	-3	Ac-228	0.922

Figure L-4 VSP Data Cut from Table L-2 and Pasted Above (Operation Example)

Rather than import all samples to a single project, two project files were established to analyze uranium and thorium separately. While SADA distinguishes analytes for geostatistical analyses, VSP considers all samples in its analyses, regardless of analyte. As such, two separate imports were required. There are ways to filter the data used in these analyses, although analyte is not a provided option.

Tables L-1 and L-2 contain the minimum data needed for import and analysis in VSP and SADA formats .vsp and .sda.

Table L-1 Sample Bi-214 Data Set for Case Study

Northing	Easting	Depth	Name	Value
185.0	60.5	-6	Bi-214	0.726
255.8	531.8	-4	Bi-214	5.53
258.9	506.1	-5	Bi-214	90.2
273.2	345.2	-4	Bi-214	0.983
164.3	337.6	-5	Bi-214	0.728
285.5	562.5	-4	Bi-214	5.52
305.6	574.0	-4	Bi-214	12
350.4	465.3	-5	Bi-214	1.11

Northing	Easting	Depth	Name	Value
377.6	432.6	-3	Bi-214	0.724
169.7	447.7	-3	Bi-214	1.25
107.0	493.2	-3	Bi-214	1.02
10.5	397.4	-4	Bi-214	13.7
353.9	479.0	-5	Bi-214	0.753
326.2	544.4	-4	Bi-214	3.62
242.0	727.8	-3	Bi-214	0.61
231.9	746.8	-4	Bi-214	0.966
255.2	642.4	-3	Bi-214	3.05
201.0	579.4	-4	Bi-214	0.637
393.8	179.2	-4	Bi-214	1.73
457.7	114.0	-3	Bi-214	0.83
409.5	129.3	-3	Bi-214	0.546
426.9	101.4	-4	Bi-214	0.603
329.5	563.3	-4	Bi-214	88.6
323.7	577.5	-3	Bi-214	64
315.2	595.3	-4	Bi-214	10.2
306.6	614.7	-3	Bi-214	10
299.6	631.8	-3	Bi-214	9.16
311.6	558.8	-4	Bi-214	3.72
301.8	549.7	-4	Bi-214	3.34
293.6	591.5	-4	Bi-214	61.5
283.3	609.9	-4	Bi-214	36.6
281.1	586.3	-4	Bi-214	107
324.7	526.1	-6	Bi-214	0.983
275.0	626.9	-3	Bi-214	4.52
282.4	527.4	-4	Bi-214	18.6
278.7	549.8	-4	Bi-214	50.5
275.5	578.7	-3	Bi-214	66.5
254.0	602.1	-3	Bi-214	6.73
295.4	568.3	-4	Bi-214	11.2
248.1	510.6	-4	Bi-214	77.2
248.1	510.6	-5	Bi-214	24.2
129.8	334.7	-4	Bi-214	0.841

Table L-2 Sample Ac-228 Data Set for Case Study

Northing	Easting	Depth	Name	Value
185.0	60.5	-6	Ac-228	1.01
255.8	531.8	-4	Ac-228	26.8
258.9	506.1	-5	Ac-228	728
273.2	345.2	-4	Ac-228	1.24
164.3	337.6	-5	Ac-228	0.877
285.5	562.5	-4	Ac-228	75.1
305.6	574.0	-4	Ac-228	98.4
350.4	465.3	-5	Ac-228	1.65
377.6	432.6	-3	Ac-228	1.11

Northing	Easting	Depth	Name	Value
169.7	447.7	-3	Ac-228	1.41
107.0	493.2	-3	Ac-228	2.23
10.5	397.4	-4	Ac-228	107
353.9	479.0	-5	Ac-228	0.982
326.2	544.4	-4	Ac-228	20.2
242.0	727.8	-3	Ac-228	1.3
231.9	746.8	-4	Ac-228	1.46
255.2	642.4	-3	Ac-228	10.6
201.0	579.4	-4	Ac-228	0.883
393.8	179.2	-4	Ac-228	1.81
457.7	114.0	-3	Ac-228	1.17
409.5	129.3	-3	Ac-228	0.922
426.9	101.4	-4	Ac-228	0.939
329.5	563.3	-4	Ac-228	921
323.7	577.5	-3	Ac-228	815
315.2	595.3	-4	Ac-228	28.6
306.6	614.7	-3	Ac-228	137
299.6	631.8	-3	Ac-228	21.4
311.6	558.8	-4	Ac-228	17.2
301.8	549.7	-4	Ac-228	15.7
293.6	591.5	-4	Ac-228	201
283.3	609.9	-4	Ac-228	299
281.1	586.3	-4	Ac-228	905
324.7	526.1	-6	Ac-228	1.54
275.0	626.9	-3	Ac-228	14.7
282.4	527.4	-4	Ac-228	85.7
278.7	549.8	-4	Ac-228	491
275.5	578.7	-3	Ac-228	232
254.0	602.1	-3	Ac-228	11.8
295.4	568.3	-4	Ac-228	63.5
248.1	510.6	-4	Ac-228	604
248.1	510.6	-5	Ac-228	235
129.8	334.7	-4	Ac-228	1.27

L.3 Preliminary Statistics and Posting Plots

The first analyses that are generally performed on a data set are basic univariate statistics and a posting plot. These are shown in Figure L-5 for Ac-228 in VSP and Figure L-6 for Bi-214 in VSP, and the corresponding information is shown in Figures L-7 and L-8 for SADA.

n =	42	Percentiles:	
Min =	0.877	1%:	0.877
Max =	921	5%:	0.889
Range =	920.12	10%:	0.952
Mean =	147.3	25%:	1.293
Median =	16.45	50%:	16.45
Variance =	69642	75%:	153
Std Dev =	263.9	90%:	690.8
Std Error =	40.72	95%:	891.5
Interquartile Range =	151.71	99%:	921
Skewness =	2.0328		

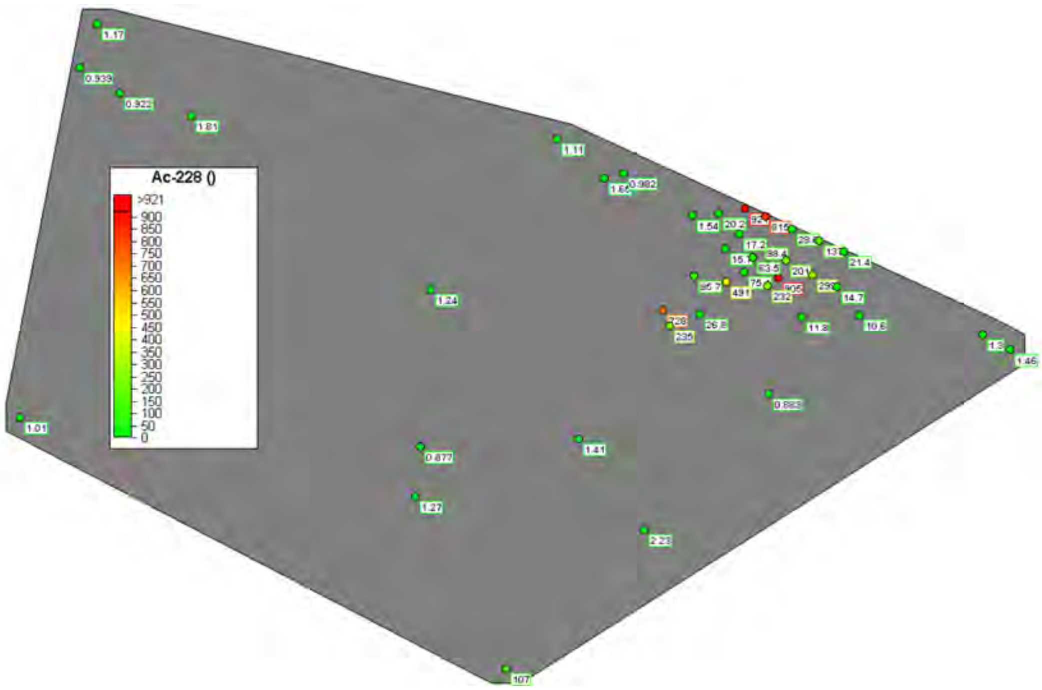


Figure L-5 VSP Preliminary Statistics and Posting Plot for Ac-228

n =	42
Min =	0.546
Max =	107
Range =	106.45
Mean =	19.101
Median =	4.12
Variance =	881.16
Std Dev =	29.684
Std Error =	4.5804
Interquartile Range =	19.065
Skewness =	1.7118

Percentiles:

1%:	0.546
5%:	0.604
10%:	0.663
25%:	0.935
50%:	4.12
75%:	20
90%:	73.99
95%:	89.96
99%:	107

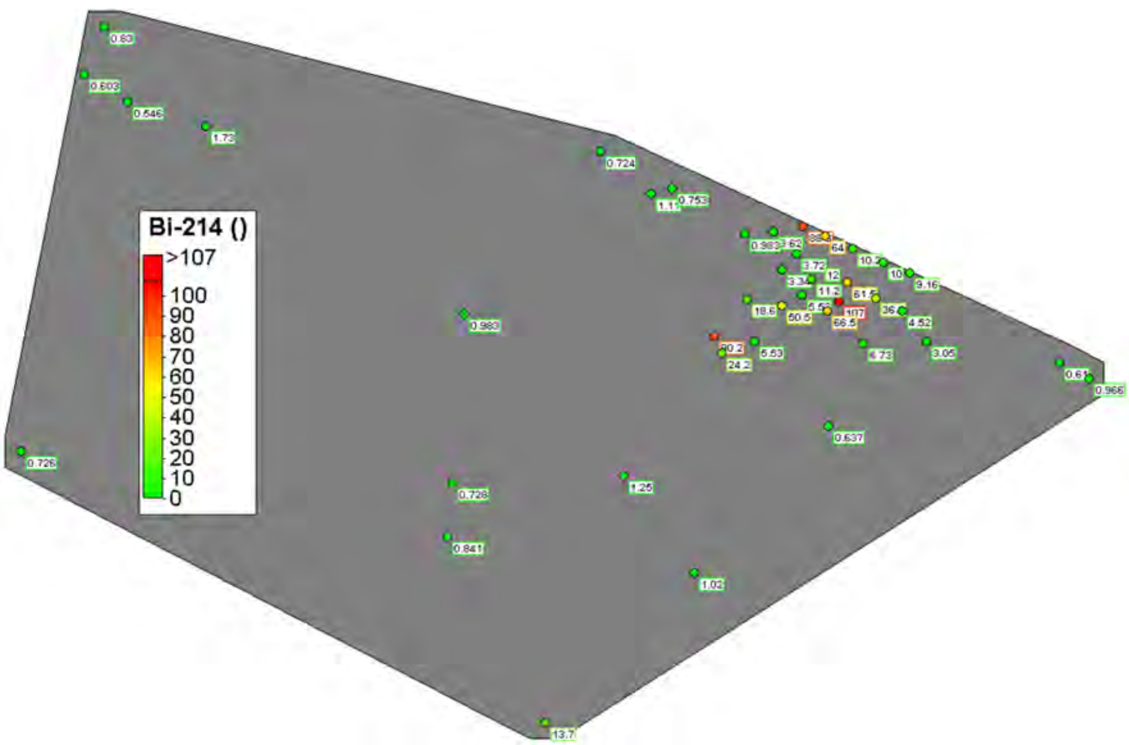


Figure L-6 VSP Preliminary Statistics and Posting Plot for Bi-214

The top figure shows the lack of variability compared to Ac-228. In the lower figure, legend properties were changed to better show variability

Analyte	N	Mean	Coefficient of Variance	Interquartile Range	UCL95 (Normal- Student's t)	Minimum Overall	Maximum Overall
Ac-228	42	147.29769	1.791595	120.715	215.826979	0.877	921

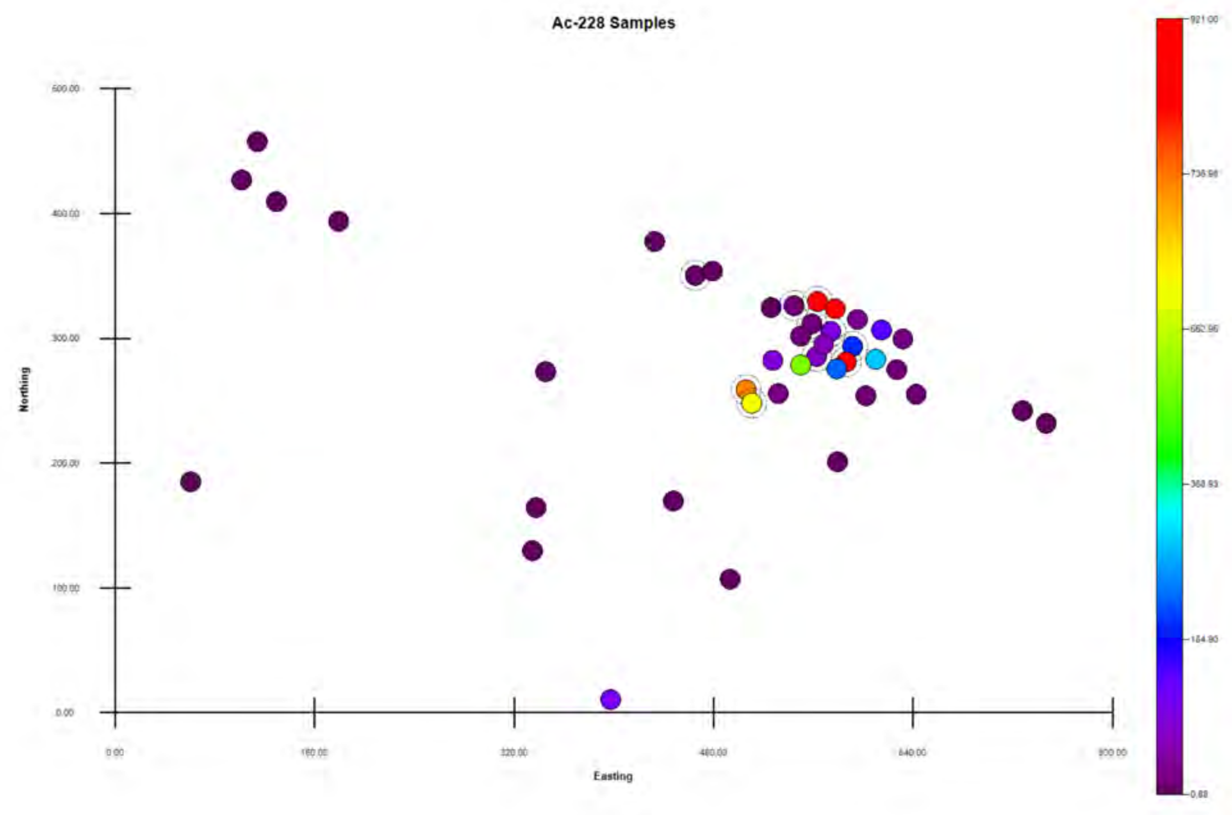


Figure L-7 SADA Posting Plot for Ac-228

Analyte	N	Mean	Coefficient of Variance	Interquartile Range	UCL95 (Normal- Student's t)	Minimum Overall	Maximum Overall
Bi-214	42	19.100714	1.554095	15.2465	26.809172	0.546	107

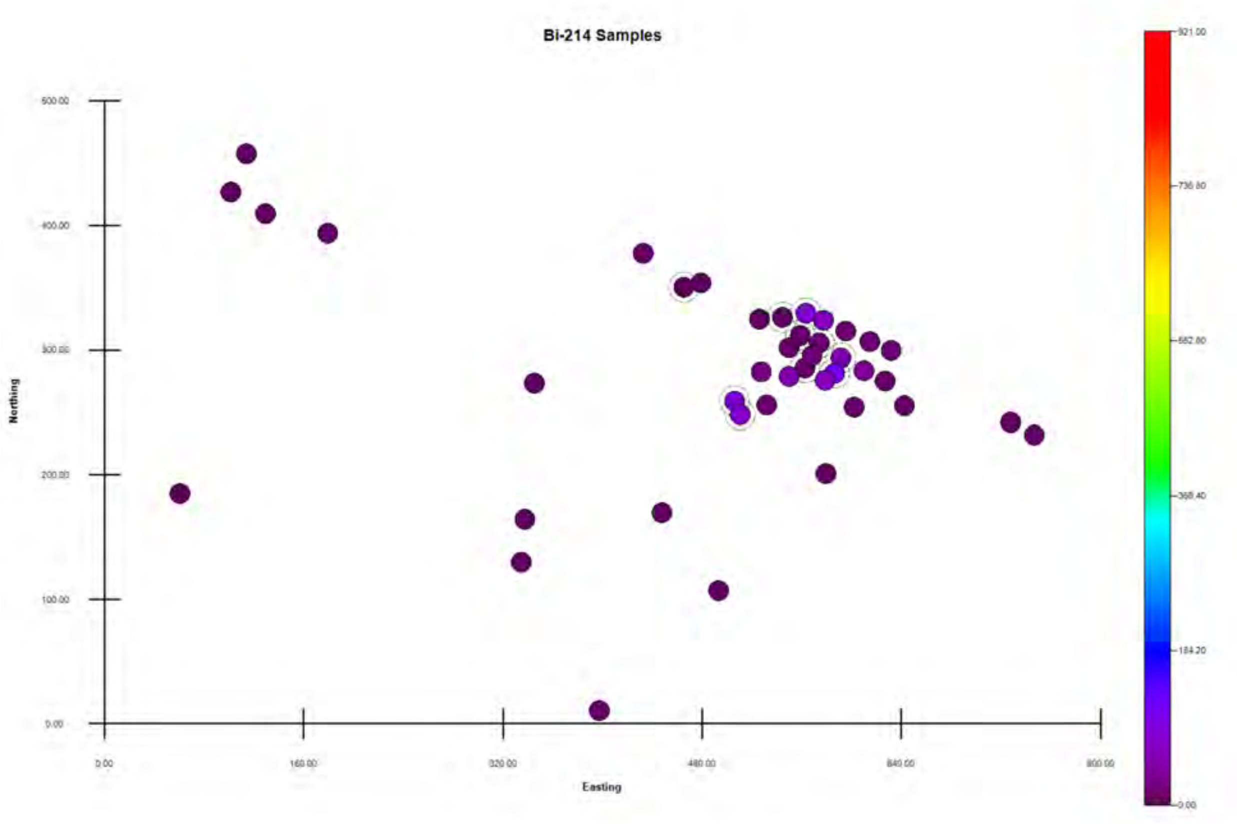


Figure L-8 SADA Posting Plot for Bi-214

As Figures L-5-L8 show, SADA and VSP return the same summary statistics. For both programs, the mean concentration for Ac-228 is 147.9 picocuries per gram (pCi/g) and the mean concentration of Bi-214 is 19.1 pCi/g. In terms of generating summary statistics, SADA and VSP have similar capabilities, including being able to generate summary statistics for a single set of analytes if multiple are present.

L.4 User Interface and Graphics

VSP and SADA were both created to assist with the evaluation of environmental data—VSP for survey planning and SADA for risk analysis. Over time, additional modules were added until they both became very large and complex programs that require a substantial effort to train users in their capabilities. Periodic short training courses are still available for VSP, and similar support was offered for SADA until about 2012. Both pieces of software have very detailed user’s guides and help files.

The two codes have different graphical user’s interfaces (GUIs). VSP is more traditional, with drop-down menus that lead the user through defining the objective of sampling and analyses of survey designs for the number and placement of samples. SADA has its GUI focused on a series of “interviews” for defining the purpose of the additional samples. VSP leans towards the initial sample planning, while SADA stresses secondary supplementary sampling to fill data gaps where they are identified. These are not mutually independent goals, but perhaps more complementary. For both SADA and VSP, particular data analyses may be difficult to find through the menus. Figure L-9 shows an example of the choices under the MAP dropdown menu in VSP.

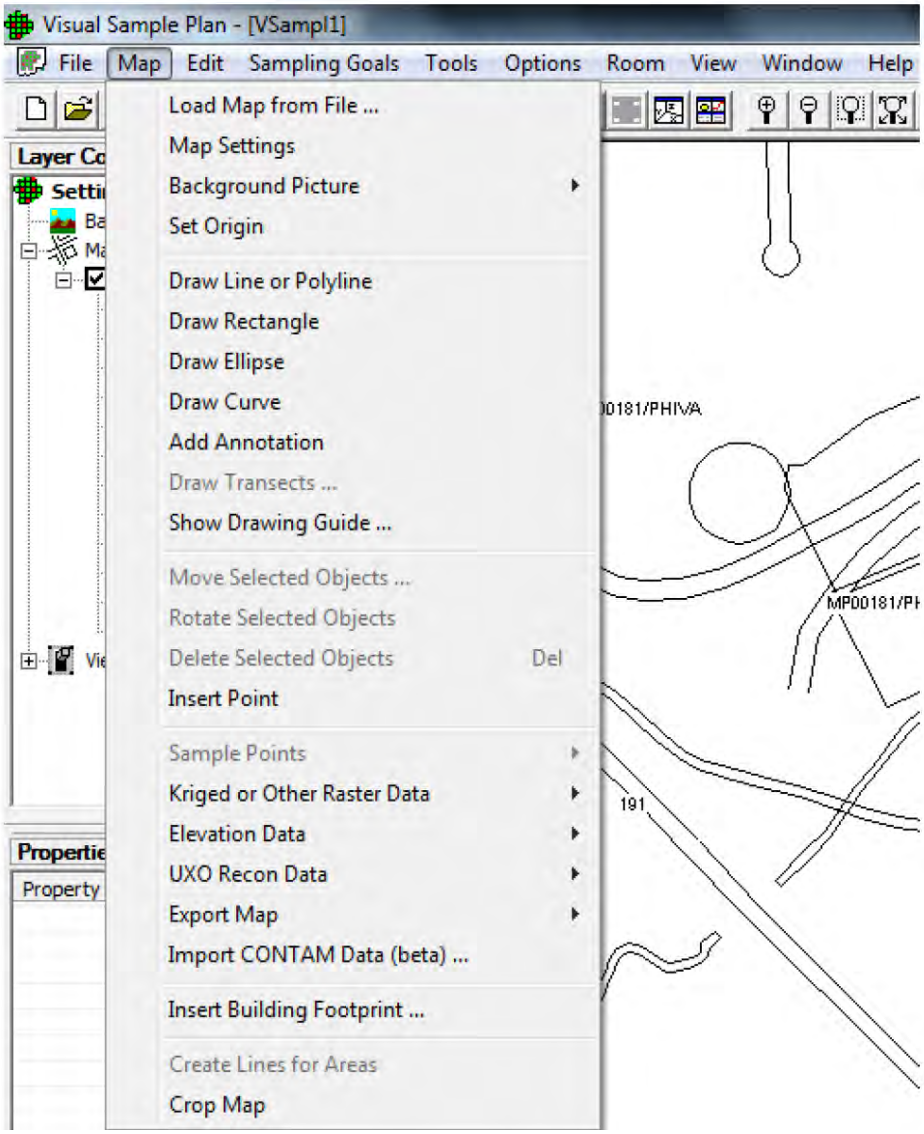


Figure L-9 MAP Dropdown Menu (Figure 2.4 in Matzke et al. 2014)

Figure L-10 shows an example using the case data in SADA. Under “Develop a sampling design,” a list of the steps necessary is shown on the left-hand side and the parameters needed to accomplish the steps are shown on the right-hand side. This process is intended to make the choices more transparent. In VSP, the same is done by choosing “Ask an Expert Mentor” (Figure L-11).

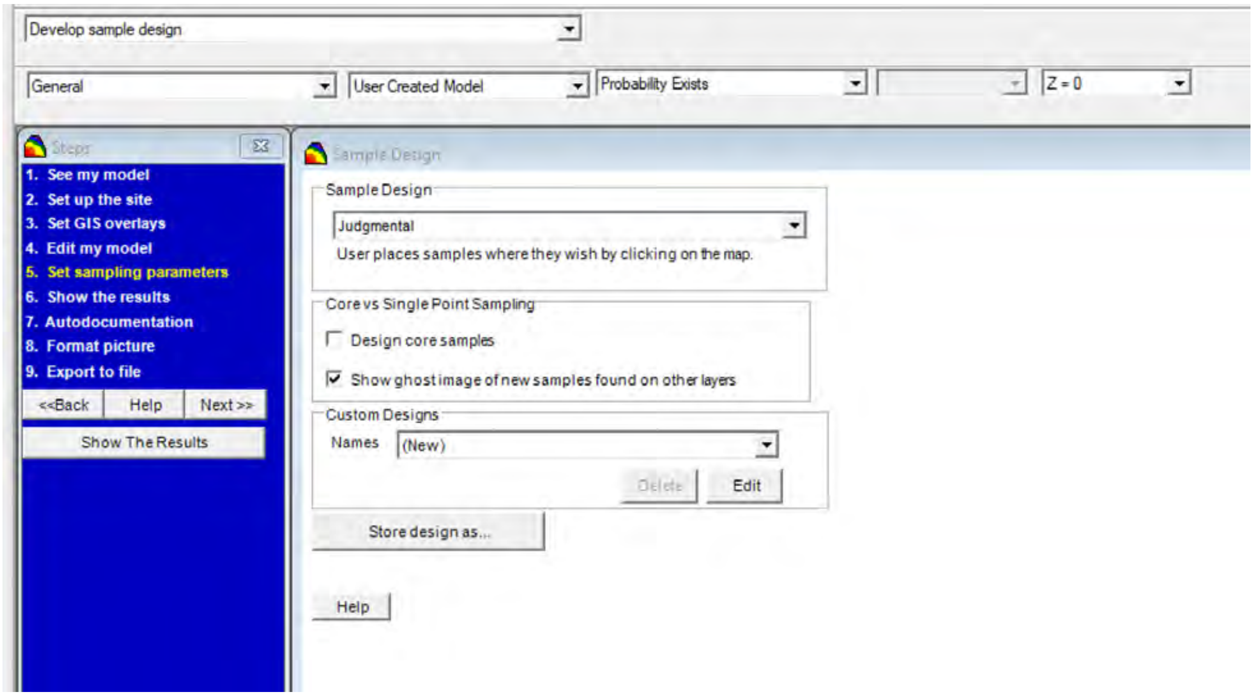


Figure L-10 SADA, Steps under the Choice of "Develop sample design," "Set sampling parameters"

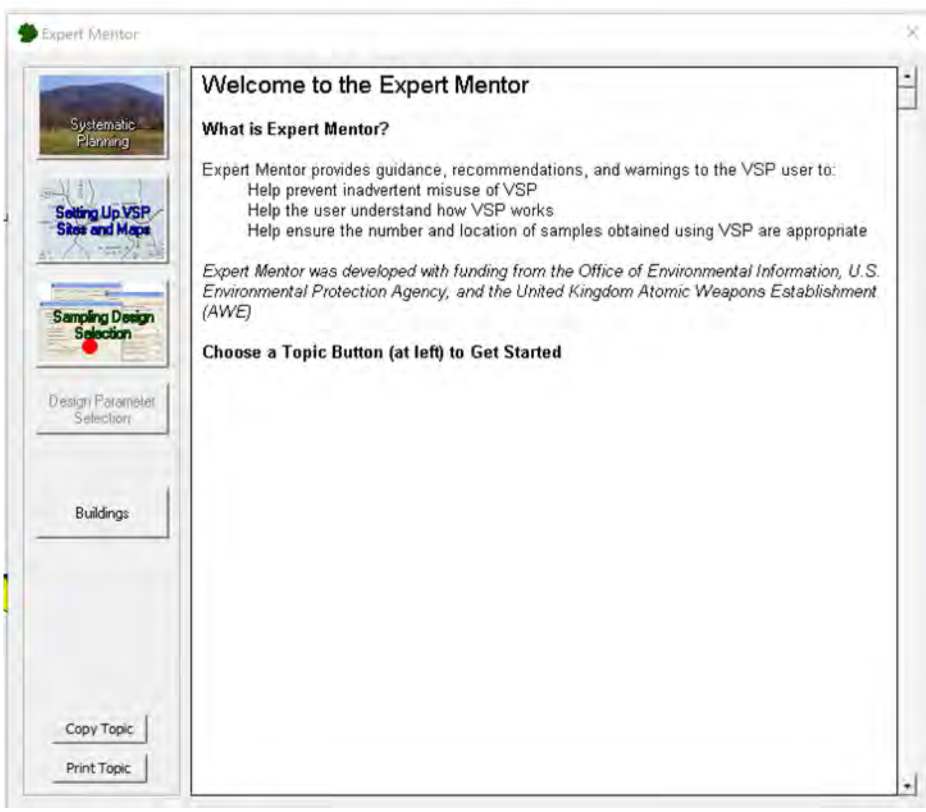


Figure L-11 VSP "Ask an Expert Mentor" dialog

L.5 Data Interpolation

Both VSP and SADA contain methods for interpolating the data and producing maps of estimated data values across the site. There are many methods of interpolation, often involving a weighted average of nearby measurement locations. Such maps can be used in subsurface surveys to estimate where additional samples should be taken, finding boundaries for contaminants of concern, and updating the probability of exceeding action levels, among others.

Inverse distance-weighted interpolation is referred to as deterministic because it is directly based on the surrounding measured values or on specified mathematical formulas that determine the smoothness of the resulting surface. Geostatistical interpolation methods such as kriging consist of models that include correlation between data values at nearby locations.

Comparing kriging as implemented in VSP and SADA is more complicated. The details of how each survey planning tool implements kriging are needed, especially when deciding to use default "recommended values" of kriging parameters. Treatment of locations outside the envelope of measurement locations may be important, especially if the data are log transformed because there may be zero values. Cross-validation can be used to evaluate different interpolation methods. One by one, locations are dropped from the kriging and the prediction of that location's interpolated value is obtained. Since the true value is "known," a mean square error is obtained. This is done for each location one at a time until a sum of mean square error is obtained. There are some methods to make this process less cumbersome, but this is beyond the scope of the present white paper. Some discussion of cross-validation appears in the SADA version 5 user guide.

The available interpolation options in VSP and SADA have inverse square distance and kriging in common. Section L.6 discusses kriging in VSP and SADA. These were investigated using the Ac-228 imports shown in L.3 due to the greater variability shown in the posting plot analysis.

The steps needed to obtain interpolated maps in VSP are shown below:

VSP: Tools → Spatial Analysis → Create Interpolated Survey Map

The steps needed to obtain interpolated maps in SADA are shown below:

SADA: Select Interpolate My Data from Interview Box Dropdown → 5. Interpolation Methods → Select Inverse Distance from Dropdown

The results produced by each are indicative of each platform's current modeling capabilities. VSP does not currently support 3D analysis even though it supports the import of 3D data. When a user attempts to use VSP's Geostatistical Analysis toolkit after loading 3D data, a warning appears indicating VSP will only use samples on floor or ground surfaces (Figure L-12). While this does not trigger when attempting to create an interpolated spatial map in VSP, the results of this analysis indicate that the interpolation is 2D. Due to the 2D nature of the VSP analysis, only the first listed point in samples that share an x and y but are located at a different z will be considered for the analysis.

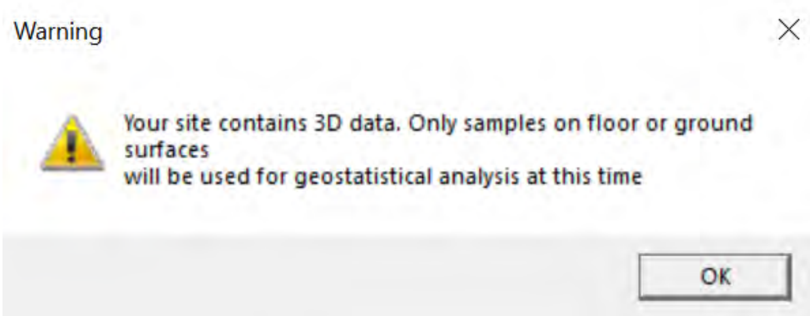


Figure L-12 VSP 3D Warning Dialogue

Setting up the interpolation in VSP is relatively simple. Only the grid size can be set by the user, otherwise VSP handles establishing the search neighborhood for the inverse square weighting.

On the other hand, SADA requires users to define the search neighborhood used in the interpolation. While SADA also provides a default set of characteristics, it was found that this set of parameters was not valid for the loaded 3D data set and instead needed to be manually adjusted. Figure L-13 shows the parameters used for the interpolation, and Figure L-14 provides an excerpt of SADA's help documentation for defining a neighborhood. Through this additional parameter-setting capacity, users can set a vertical search radius, which provides a 3D interpolation as compared to VSP's 2D interpolation.

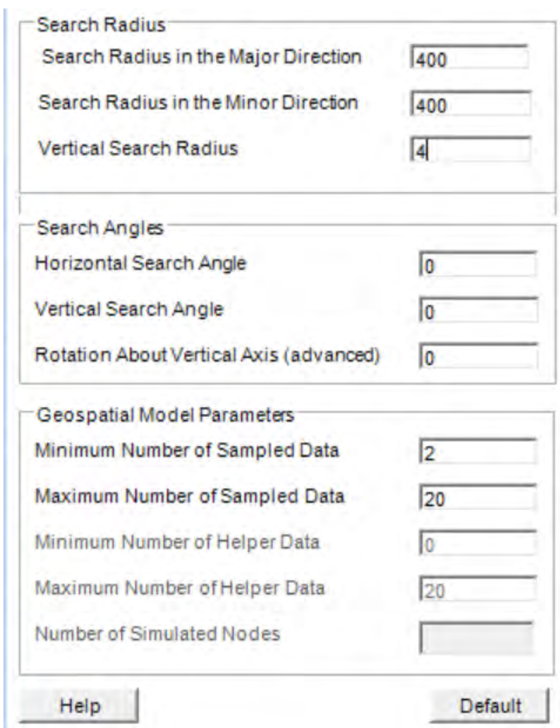


Figure L-13 SADA Search Neighborhood Parameters

Defining a Neighborhood

Inverse distance, ordinary kriging, and indicator kriging interpolation methods all require a neighborhood definition for estimating concentration values at a point. A neighborhood is defined as an area around the point in which data values will be used to estimate the concentration value. Data values outside the neighborhood will be excluded.

The neighborhood is always defined by a *search ellipse* that can be manipulated in shape, size, and orientation to include or exclude various data. The parameters that control the shape and size of the search ellipse are found when selecting **Search Neighborhood** from the Steps Window. (See Search Neighborhood.)

The parameters Major Radius, Minor Radius, and XY Angle control the size and shape of the search ellipse.

Horizontal Search Angle

The angle or direction of the *major elllipse* axis. This angle is measured clockwise from the positive Y axis (0 deg is North). The *minor elliptical* axis is perpendicular to the major axis.

Search Radius in the Major Direction

The radius of the ellipse along the major axis.

Search Radius in the Minor Direction

The radius of the ellipse along the minor axis.

The following schematic demonstrates the roles of these parameters in the XY plane.

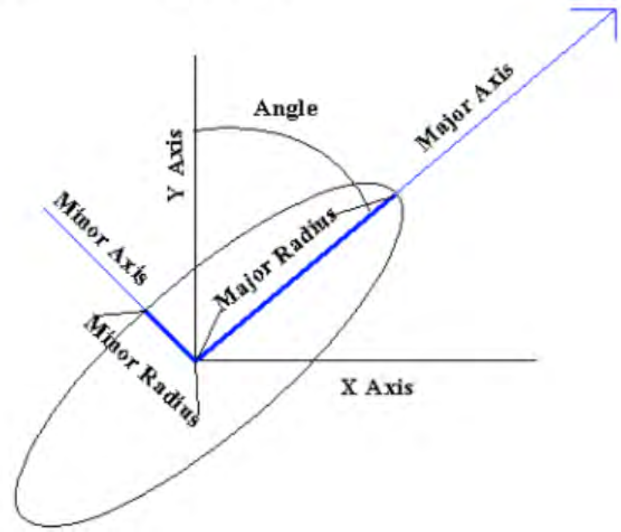


Figure L-14 Defining a Search Neighborhood in SADA

Source: https://www.sadaproject.net/helpv4/defining_a_neighborhood.html

Figures L-15 and L-16 show VSP inverse square weighting for Ac-228, and Figure L-17 shows SADA inverse square weighting for Ac-228. Most notably, the central hotspot of approximately 750 pCi/g that appears in the VSP interpolation is not represented in SADA's inverse square weighting. This is due to SADA's 3D search neighborhood capturing a far greater number of zero values in 3D than is captured in VSP's 2D search. Meanwhile, the northeast hotspot is represented in both, although not to as great an intensity in SADA as in VSP. Ultimately, while there may be some qualitative similarity between SADA's 3D interpolation and VSP's 2D interpolation, comparing the two results is not straightforward and requires considerable understanding of the data being imported and how these programs handle those data to appropriately assess the results.

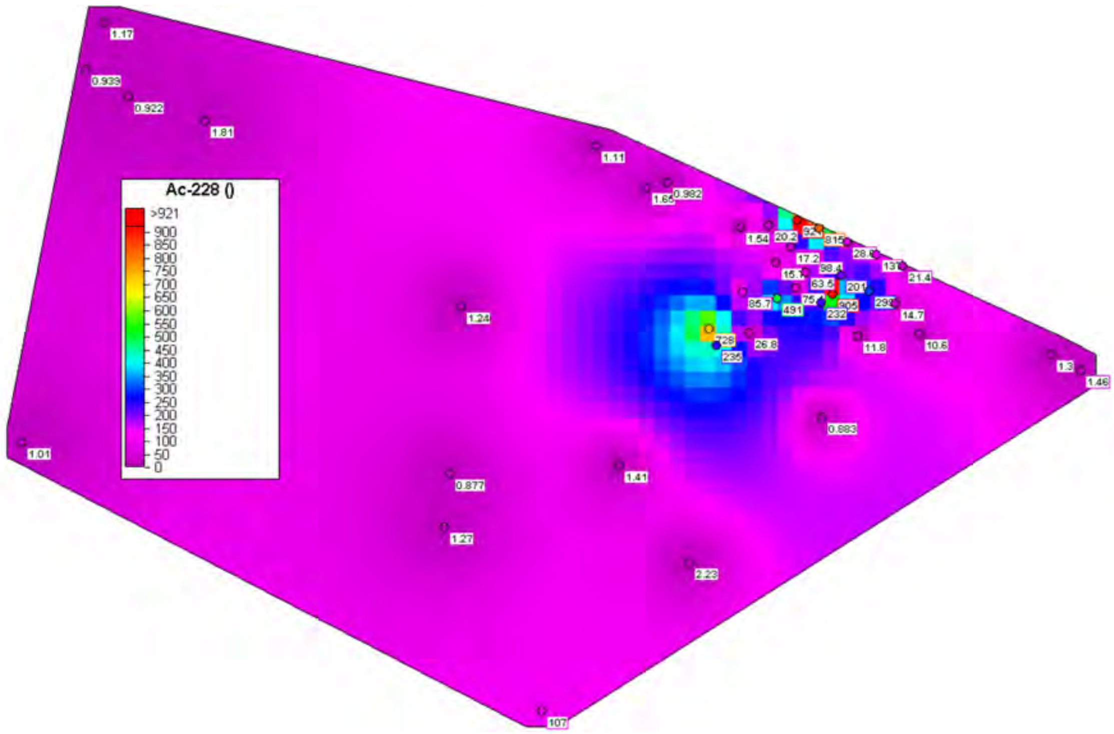


Figure L-15 VSP 10-Foot Cell Inverse Square Weighting

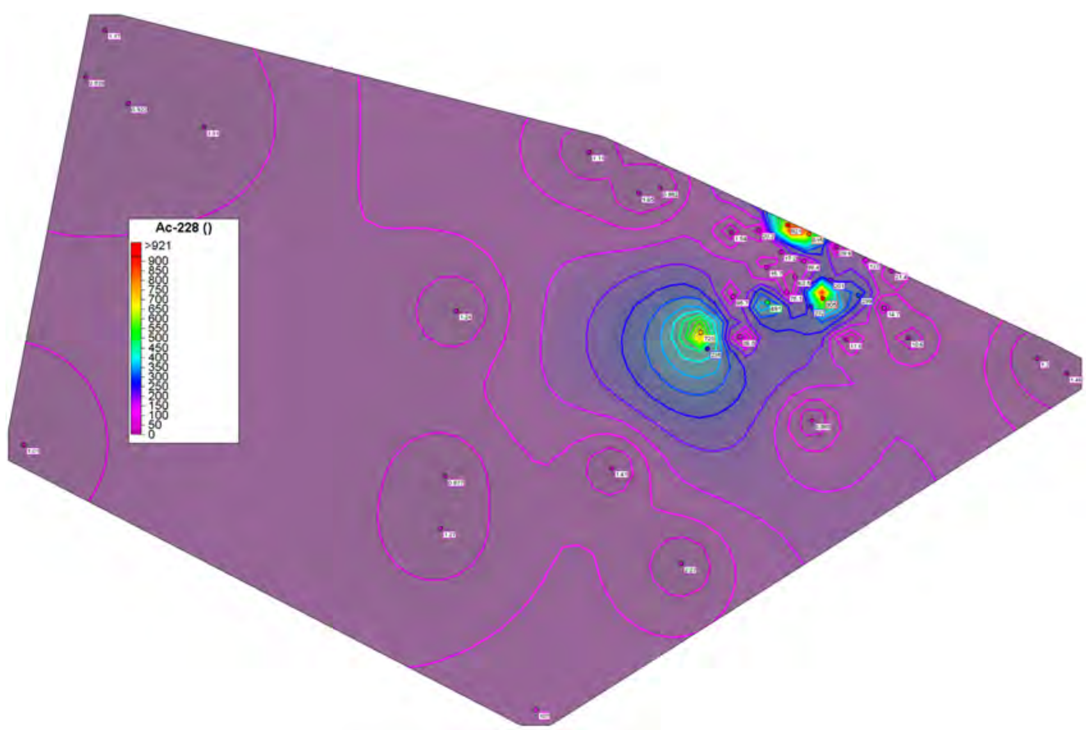


Figure L-16 VSP 10-Foot Cell Inverse Square Weighting Contours Ac-228

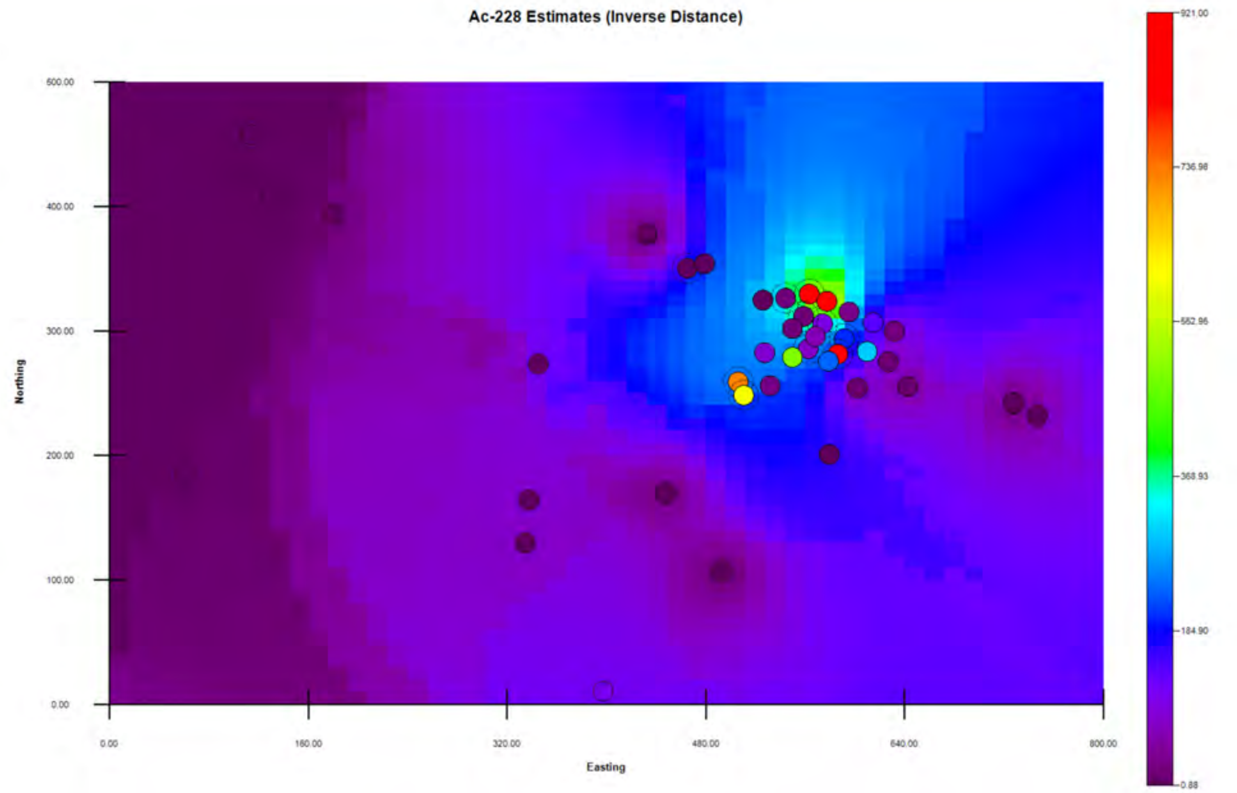


Figure L-17 SADA Ac-228 Inverse Square Distance

L.6 Kriging

L.6.1 Kriging in SADA

Implementation of kriging requires a fit to the data of a correlation model in the form of a semivariogram. SADA has a module for correlation modeling, but it requires a considerable number of input parameters to the process. This module is accessed through the same route as inverse square weighting, with the exception that ordinary kriging is selected in the final dropdown instead. Figure L-18 shows the input parameter form and a fit to the semivariogram using the recommended values. Making informed judgment decisions as to the values that are appropriate requires considerable expertise and is likely to be a daunting task in the survey design. The amount of scatter in the semivariogram is the norm rather than the exception. SADA has a provision for accepting recommended values for these parameters, but the details as to how they are arrived at are not evident. Using the Graphical Edit Command Button, the shape of the variogram fit can be altered by dragging the grey boxes circled in red to other places on the figure. Generally, it is considered that the variogram at shorter distances between data points will be more important than at further distances because the weights assigned to nearer points in the interpolation will be greater than those further away. Using the variogram fitting tool, the effect of variogram changes on the ordinary kriging map can be explored. Short of acquiring the assistance of a geostatistical expert, the best a novice might achieve is likely to be the recommended parameters. Figure L-19 shows the SADA Ac-228 estimates using ordinary kriging.

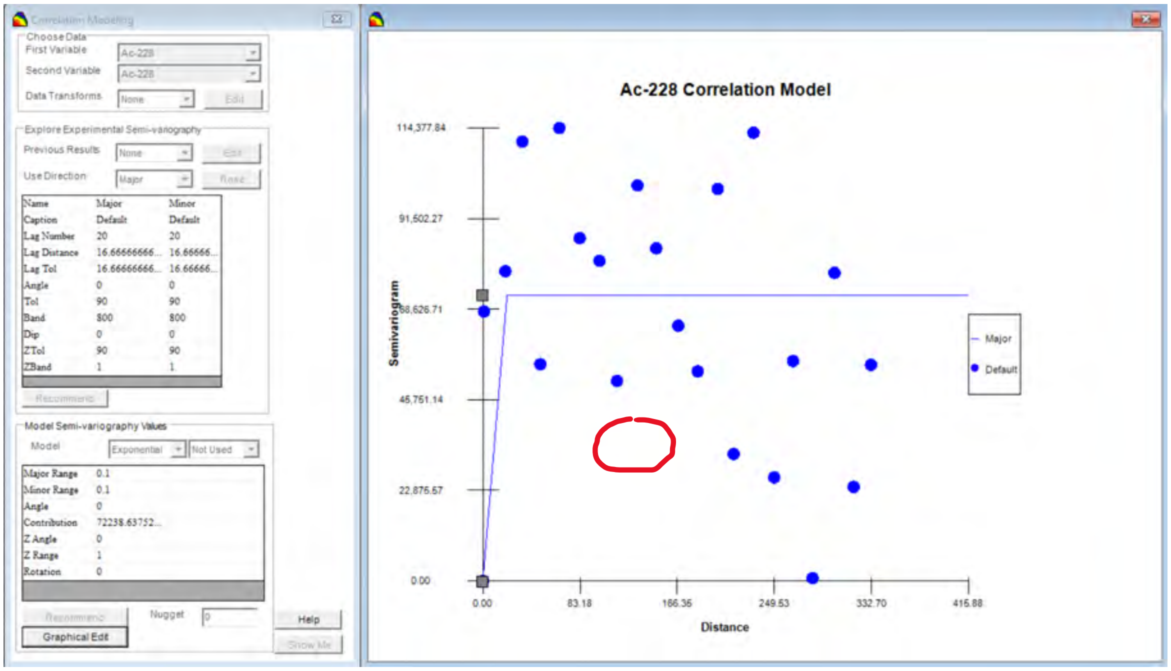


Figure L-18 SADA Ac-228 Variogram Using SADA Recommended Parameter Values

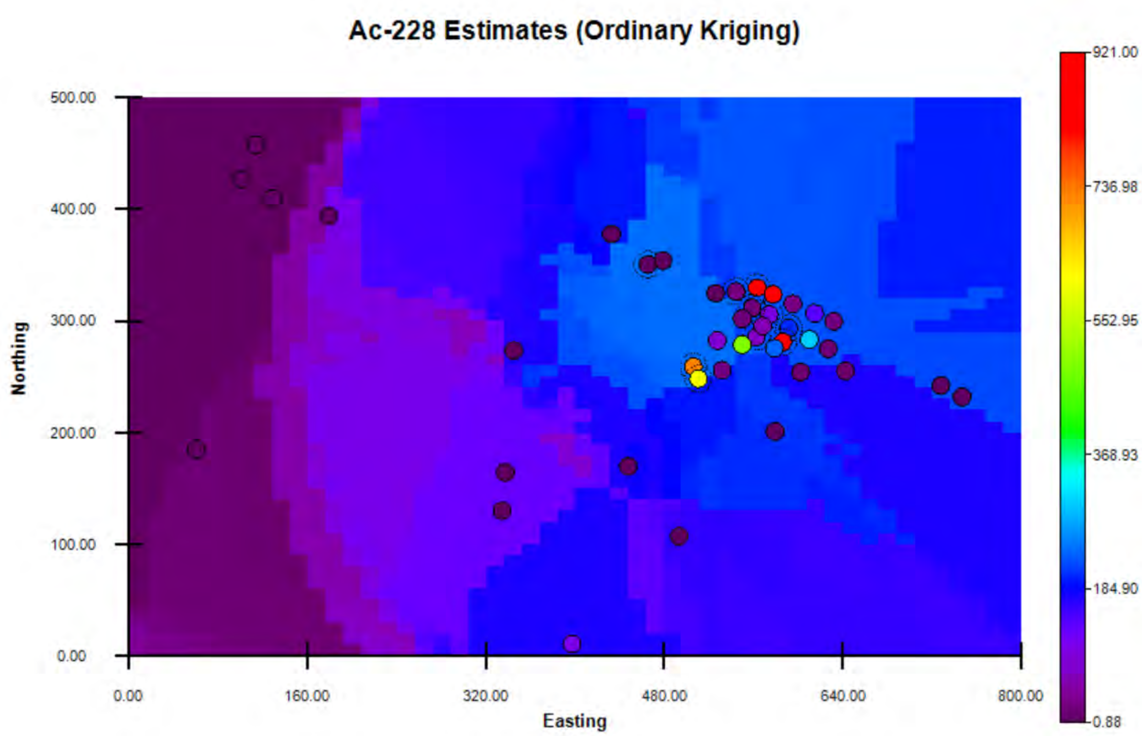


Figure L-19 SADA Ac-228 Estimates Using Ordinary Kriging

L.6.2 VSP Kriging

VSP's kriging functionality is simpler than SADA's and is limited to two dimensions. Kriging in VSP is accessed using the following steps:

Tools → Spatial Analysis → Geostatistical Analysis

The equivalent dialogue in VSP for semivariogram fitting is shown in Figure L-20. As with SADA, there is an autofit option using recommended parameter values. However, there is a more intuitive method for adjusting the fit using sliders for range and sill (in the red square in Figure L-20. Appendix D to this white paper discusses fitting variograms in more detail, including the definitions of nugget, range, and sill, as shown in Figure L-21.

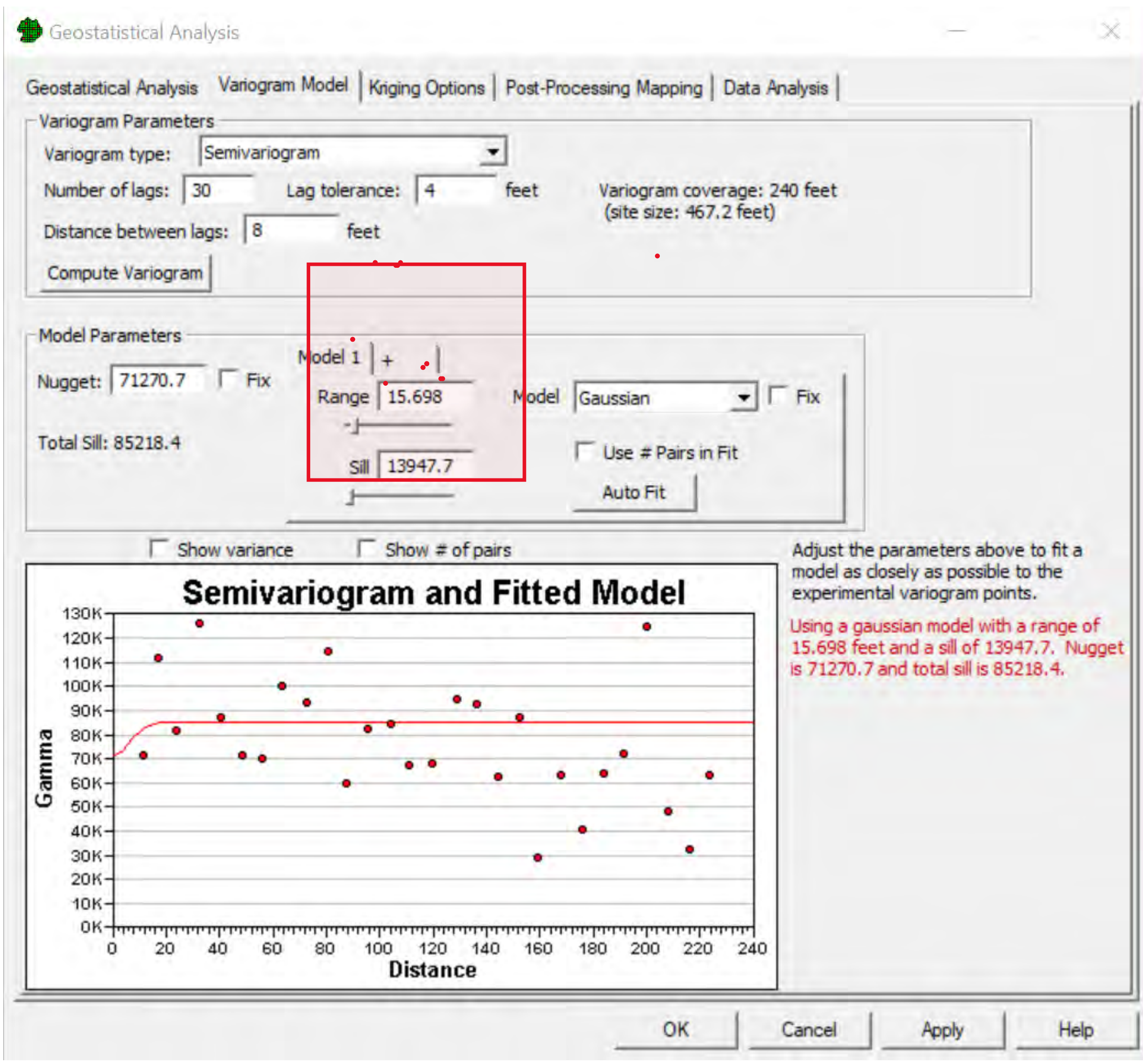


Figure L-20 VSP Ac-228 Variogram Using Recommended Parameter Values

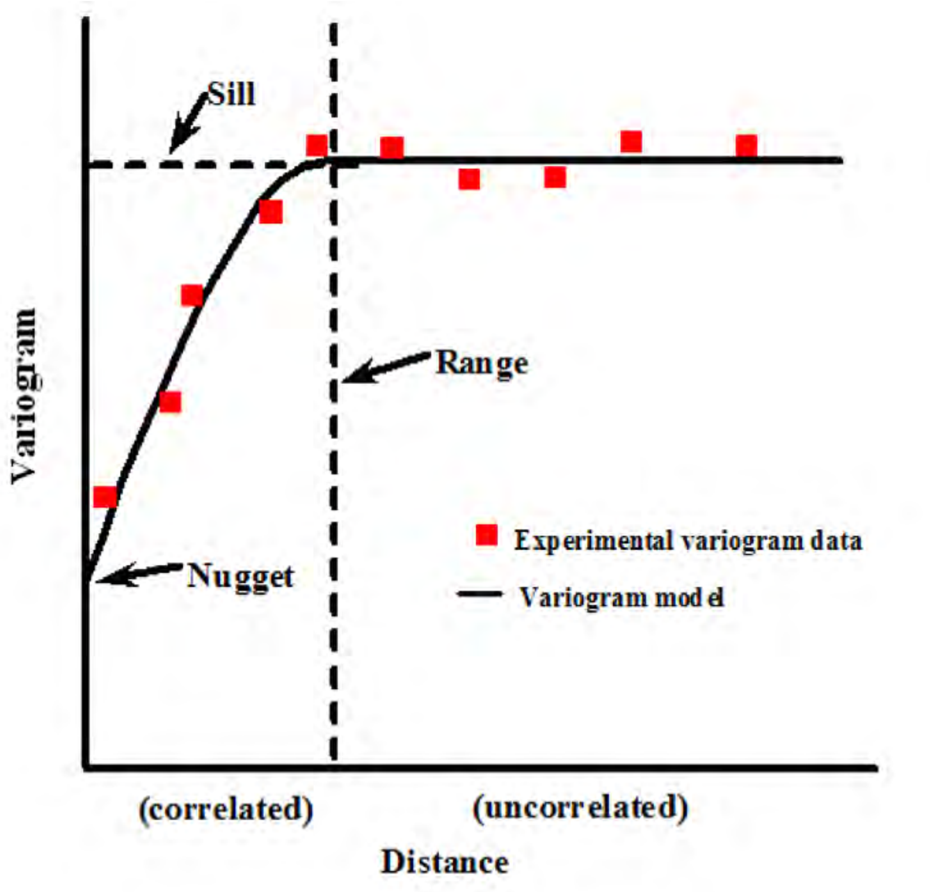


Figure L-21 Variogram Nugget, Range, and Sill

Source: https://vsp.pnnl.gov/help/Vsample/Kriging_Variogram_Model.htm

The adjacent tab in the Geostatistical Analysis dialogue uses the user-defined semivariogram parameters and additional parameters to krige the data. This analysis used the default computed values (Figure L-22). Unlike in SADA, not all cells had enough information to compute a kriged estimate, resulting in only a portion of the sample area displaying a result. Figure L-22 shows VSP Ac-228 ordinary kriging using the computed parameter values.

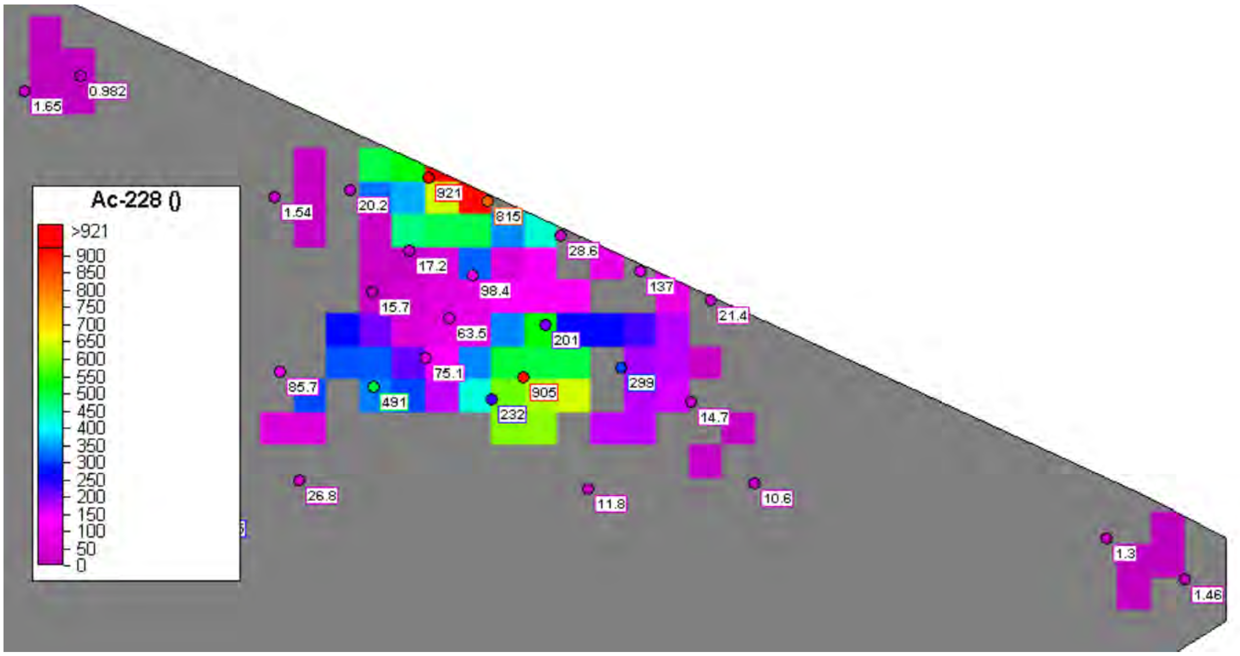


Figure L-22 VSP Ac-228 Ordinary Kriging Using Recommended Parameter Values

The simpler, more intuitive way of adjusting the fit in VSP is likely to be less daunting than the plethora of input parameters in SADA, although at the cost of a more limited geostatistical analysis. However, while a 2D model in layers is likely to be easier to work with than a 3D model where the scale of horizontal (X and Y) may be very much larger than in the vertical (depth), modeling multiple layers may result in data gaps, as seen with VSP's kriging, that would have to be further rectified. Another simplification for 2D would be obtained when the variogram in any direction of the X,Y plane is the same (i.e., isotropy can be assumed).

L.7 Bayesian Ellipgrid and Markov-Bayes

Following the directions in the SADA user guide (Stewart et al. 2009; Chapter 41, page 539) leads to a point where some of the steps needed to obtain the sample design are not fully implemented; notably, the Bayesian Ellipgrid sample design is missing from the Sample Design dropdown. It was expected that this could form a solid basis for the number of samples needed; however, this is not currently possible in the most recent version of SADA.

In several cases, sample designs in NUREG/CR-7021, "A Subsurface Decision Model for Supporting Environmental Compliance," Chapter 7, issued January 2012 (NRC 2012), and in the Geospatial-Based Decision Framework for Extending MARSSIM Regulatory Principles into the Subsurface (GEM) (Stewart 2011) discussed in Appendix M to this white paper were implemented in prototype versions of SADA version 6, but they were not contained in the publicly released version 5. Similarly, steps for implementing Markov-Bayes, which were contained in prototype versions of SADA version 6, are not contained in SADA version 5 (Stewart et al. 2009, p. 422).

VSP has an extensive implementation of Ellipgrid, so the extension to Bayesian Ellipgrid should be straightforward. This is a recommended area of further study.

L.8 Conclusions

The scope of the study described in this appendix was an examination of the current capabilities of SADA and VSP using a set of actual data values, but with the actual sample locations in relative terms only to keep the identity of the site anonymous. This white paper identified examples of possible approaches using VSP and SADA as two of the best alternatives for building approaches for designing and evaluating subsurface survey units.

VSP appears to have a more approachable user interface. However, while VSP can handle data analysis in 2D layers across multiple files, SADA can be set up to perform analyses in three dimensions within a single file. Although SADA has a much broader geostatistical scope than VSP, it may be difficult to bring to a usable product as SADA is not currently supported or maintained. To move forward with SADA is likely to be far more time consuming and expensive. This suggests that more focused advances for subsurface implementation of VSP would be more successful.

L.9 References

Matzke, B.D., J.E. Wilson, L.L. Newburn, S.T. Dowson, J.E. Hathaway, L.H. Sego, L.M. Bramer, and B.A. Pulsipher (2014). “Visual Sample Plan Version 7.0 User’s Guide,” Pacific Northwest National Laboratory Report (PNNL)-23211, Richland, WA, 2014. https://vsp.pnnl.gov/docs/PNNL-23211.pdf

Stewart, R., Welsh, C., Purucker, T., and Stewart, D. (2009). “An Introduction to Spatial Analysis and Decision Assistance (SADA), Environmental Applications for Version 5, User Guide,” University of Tennessee, Knoxville, TN, December 19, 2009. https://www.sadaproject.net/documentation.html

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U.S. Nuclear Regulatory Commission (2012). “A Subsurface Decision Model for Supporting Environmental Compliance,” NUREG/CR-7021, prepared by University of Tennessee, Knoxville, TN, for NRC Office of Nuclear Regulatory Research, Washington, DC, January 2012.

U.S. Nuclear Regulatory Commission (2000). “Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM),” NUREG 1575, Revision 1; EPA 402-R-97-016, Revision 1; DOE/EH 0624, Revision 1; U.S. Department of Defense; U.S. Department of Energy; U.S. Environmental Protection Agency; and U.S. NRC; Washington, DC, August 2000, ADAMS Accession No. ML003761445.

APPENDIX M

SUMMARY OF STEWART (2011)

Table of Contents

Figures

Tables

M.1 Geospatial Extension to MARSSIM

The material in this appendix summarizes the dissertation of Robert N. Stewart, "A Geospatial Based Decision Framework for Extending MARSSIM Regulatory Principles into the Subsurface," issued 2011 (Stewart 2011). It is meant to provide the reader with a condensed version of the material covering most of the main points of the dissertation.[1] It has been developed with the author's consent, and text and figures are used with permission.

The Multi-Agency Radiological Site Survey and Investigation Manual (MARSSIM) provides detailed guidance for planning, implementing, and evaluating environmental and facility radiological surveys that are conducted to demonstrate compliance with a dose- or risk-based regulation. MARSSIM's objective is to describe a consistent approach for planning, performing, and assessing building surface and surface soil final status surveys to meet established dose- or risk-based release criteria, while at the same time encouraging an effective use of resources. Compliance is determined by comparing radiological measurements to established limits using a combination of hypothesis testing on the mean of laboratory samples or direct measurements at point locations, or both, and scanning measurements. Scanning allows investigators to identify localized pockets of contamination missed during sampling. Unfortunately, unless the radiation emitted by the material reaches the surface where it can be measured, scanning for subsurface residual radioactivity is not possible, and the direct application of MARSSIM breaks down.

The Geospatial Extension to MARSSIM (GEM) proposed by Stewart (2011) provides a method of subsurface decision support in the absence of subsurface scanning technologies. Based on geostatistical simulations of radiological activity, GEM recasts the decision rule as a multiscale geospatial decision rule called the *regulatory limit rule* (RLR). The RLR requires simultaneous compliance with all scales and depths of interest at every location throughout the site. The RLR is accompanied by a compliance test called the *stochastic conceptual site model* (SCSM). For those sites that fail compliance, a remedial design strategy is developed, called the *Multi-scale Remedial Design Model (MrDM)*, that spatially indicates volumes requiring remedial action. MrDM is accompanied by a sample design strategy known as the *Multi-scale Remedial Sample Design Model (MrsDM)* that refines this remedial action volume through careful placement of new sample locations. Finally, a new sample design called *Check and Cover* can support early sampling efforts by directly using prior knowledge about where contamination may exist.

As with MARSSIM Revision 1 (NUREG-1575, "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)," issued August 2000 (NRC 2000)), GEM contains a number of novel terms that must be understood in order to apply it. It will require preparation of a carefully designed roadmap, software tools, and training materials to be useful. The mathematics of GEM are not trivial, and a number of simplifying assumptions and rules of thumb should be developed, if possible, to broaden the user base.

Many of the terms defined and used in MARSSIM will have analogs in GEM. Geostatistical simulation permits calculation that a decision criterion is exceeded at any scale and allows inclusion of cheaper, faster field measurements, an activity emphasized by the U.S. Environmental Protection Agency's (EPA's) Triad approach. The major additions to the subsurface toolbox are geostatistical in nature. In many cases, this might be judged equivalent to some sort of kriging. The most important part of GEM is that it uses geostatistical simulations to estimate the probability distribution of residual radioactivity concentrations at (potentially) any location in the site, surface or subsurface. This is somewhat analogous to the use of bootstrapping or resampling. When using simulations to model concentrations at many

[1] An important reference for the geostatistical methods in this work is Goovaerts (1997).

locations, one quickly runs into computational issues. It may take several hours to examine one instance (Stewart 2011).

A prototype of GEM is implemented within the Spatial Analysis and Decision Assistance (SADA) software (version 5) and applied to a hypothetical radiologically contaminated site to show how these tools can be used. The GEM method will fail compliance if a survey unit contains an area of any size and shape, situated anywhere within the survey area (including the survey unit itself), that exceeds an established probability of exceeding the derived concentration guideline level (DCGL).

GEM requires a geospatial model that can do both of the following:

- Model the uncertainty (probability) about exceeding a DCGL for any exposure unit situated anywhere within the study area.
- Integrate different forms of data in the model (field methods, laboratory methods, etc.) for testing the decision rule, for example by incorporating elements of the EPA Triad approach that emphasize decision quality objectives beyond data quality objectives (both referred to as DQOs) (EPA 2001).

For any location, geostatistical models treat the unknown concentration as a random variable. The probability density function and the cumulative distribution function for this random variable characterize the uncertainty:

- What is the probability that the concentration of residual radioactivity at that location is less than the DCGL?
- What is the probability that the concentration of residual radioactivity at that location lies in the interval [a,b]?

Kriging estimates a value for the concentration of residual radioactivity at a location as a weighted combination of nearby samples. Kriging is an exact interpolator. It will return the value of the residual radioactivity measured at that location. As an interpolator, it cannot return a value outside the range of the data (minimum to maximum). Finally, as a sort of moving average, the map of kriged values is smoother than reality. This will be discussed further below.

Geostatistical simulation offers an advantage over kriging. Because kriging is based on a local average of the data, it produces smoothed output. Geostatistical simulation produces better representations of the local variability because it adds the local variability that is lost in kriging back into the surfaces it generates. Geostatistical simulation generates multiple, equally probable representations of the spatial distribution of the attribute under study. These representations provide a way to measure uncertainty for the unsampled locations taken all together in space, rather than one by one (as measured by the kriging variance). Moreover, the kriging variance is usually independent of the data values and generally cannot be used as a measure of estimation accuracy. On the other hand, estimation accuracy can be measured by building distributions of estimated values for unsampled locations using multiple simulated realizations (ESRI 2022).

Figure M-1 shows the core principles of GEM and how those principles relate to MARSSIM, Triad, and geostatistics.

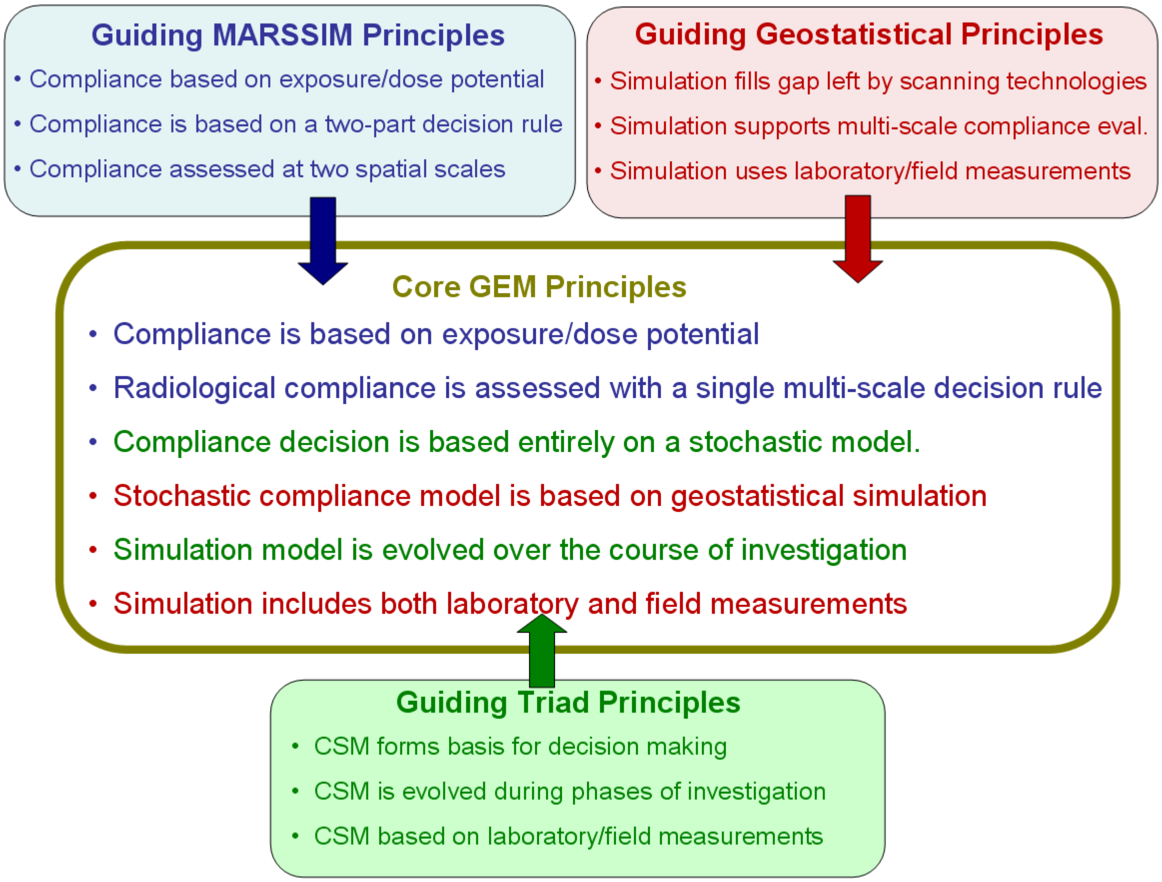

Figure M-1 Relationship of GEM to MARSSIM, Triad, and Geostatistical Simulation

Source: Stewart 2011

The GEM framework contains four interrelated methods:

(1) The regulatory limit rule (RLR) specifies the subsurface decision rule across multiple scales (analogous to the survey unit and the elevated area in MARSSIM). The RLR is a formal definition for geospatial compliance (analogous to DQO step 5 to develop a decision rule).

(2) The stochastic conceptual site model (SCSM) tests for compliance with the RLR.

(3) Multi-scale Remedial Design Model (MrDM) considers multiple decision scales (volume or area) at once in designing remedial plans

(4) Multi-scale Remedial Sample Design Model (MrsDM) identifies new sample locations that could reduce the size of the MrDM remedial design.

Each step is intended to build on the method preceding it.

Beginning with the RLR, a formal definition for geospatial compliance is established. This RLR is analogous to the action level set during the DQO process or the DCGL in MARSSIM. Using the RLR, the SCSM test determines whether compliance has been met. This is the step in the DQO process in which the decision rule (i.e., hypothesis test and desired limits on decision error rates) is specified, such as the Wilcoxon Rank Sum test or the Sign test in MARSSIM. It may also be a simple comparison to a limit like the elevated measurement comparison (EMC). MrDM considers multiple decision scales (volume or area) in designing remedial plans. For example, in MARSSIM, one scale is the survey unit, and a smaller area defined by the distance between sample locations within the survey unit is called the grid area. The $DCGL_{EMC}$ is determined by the size of the grid area. MrDM estimates the optimal remedial design that brings the site into compliance with an acceptable degree of confidence. Using MrDM, MrsDM seeks to further refine the remedial design through the careful positioning and acquisition of new samples.

The GEM decision rule extends the single decision criteria normally found in many geostatistical publications to multiple, scale-dependent criteria required for the evaluation of a continuum of exposure unit sizes situated anywhere on the site. The SCSM test is essentially a model of compliance based on geostatistical (stochastic) simulation. Using an SCSM or a geostatistical simulation model directly in the compliance decision, however, is a new approach for regulatory guidance and may lay the groundwork for a geospatial paradigm in regulatory decision-making. From this GEM decision rule, MrDM is developed by extending and modifying the methods published by Saito and Goovaerts (2003) from single to multiscale decision criteria and from a fixed set of exposure units to a continuum of exposure unit sizes and shapes that can be placed anywhere across the site.

The sample design strategy (MrsDM) accompanies the MrDM approach and follows concepts in both Demougeot-Renard et al. (2004) and Johnson (1996). Unlike either of these methods, MrsDM is a multiscale sampling strategy specifically designed to reduce uncertainty in MrDM designs. Finally, the Check and Cover design extends the method proposed by Meyer and Brill (1988) and supports early characterization efforts.

Chapter 3 of the dissertation describes the theoretical derivation of the GEM framework. Under this framework, the four interrelated methods are developed: RLR, SCSM, MrDM, and MrsDM. Each is intended to build on the method preceding it.

Chapter 4 discusses how these components are implemented within SADA. The user interface with SADA takes the form of an interview of choosing the desired result and then replying to a series of steps needed to accomplish the result by entering the important parameter values required. Table M-1 shows the steps necessary to produce an area of concern map using SADA. Much of Chapter 4 and Appendix A to the dissertation is concerned with the programming details and definitions of the Class structures in Visual Basic that were used. A summary on page 107 of the paper contains the major technical points. GEM is implemented as prototype within SADA Version 5.0 but is incomplete and not fully accessible in the public release.

Table M-1 The Interview Steps within SADA to Draw an Area of Concern Map

Step	Description
See the Data	Select the data set
Set Up the Site	Set horizontal boundaries/vertical layers
Set GIS Overlays	Permit addition of GIS files in results window
Set Grid Specs	Set horizontal grid specifications
Select Simulation Method	Permit selection of simulation approach
Choose Helper Data	Allow users to include field detection data
Correlation Modeling	Facilitate modeling of spatial autocorrelation
Search Neighborhood	Search neighborhood geometry for simulation
Specify Decision Criteria	Enter decision criteria such as GEM

Step	Description
Show the Results	Execute MrDM (if multiscale is selected)
Autodocumentation	Use SADA's report writing feature
Manage Model Results	Store remedial designs developed
Format Picture	Access graphical formatting controls
Export to File	Export results to SADA standard format

Chapter 5 of the dissertation discusses Check and Cover survey designs (Miller and Shaw 2001). Check and Cover is a new sampling strategy for incorporating expert judgment in sample designs early in characterization. This is accomplished by applying the p-median algorithm to a prior raster concern model adjusted for investigator confidence in the prior concern. As with the GEM implementation, Check and Cover is implemented as a prototype extension within SADA Version 5.0.

In designing a survey, a key question is when have enough data been collected—that is, when does one stop? In MARSSIM, decision error rates are set as an objective, and the number of samples needed to achieve them is calculated. Each additional sample increases the power of the test to detect when the null hypothesis should be rejected. Generally, as more samples are collected, the additional power provided declines. This means there is a point of diminishing returns at which the additional information gained with a sample is not worth its cost. Clearly, this is a subjective judgment. What is desired is some measure of the value of each sample (or core) taken in a survey unit.

In operations research, location planning of resources involves specifying the physical position of facilities that provide demanded services. Examples of facilities include hospitals, restaurants, ambulances, retail and grocery stores, schools, and fire stations. In the present case, the location is where a sample is taken, and the demand is the need for information to make a decision in discrete positions. The p-median problem is to place p facilities to minimize the average distance between an information-weighted demand node and the location in which a sample or core is placed. This is a vastly simplified explanation of p-median.

In essence, what is required is some metric of merit related to the information value of a sample monotonic (either increasing or decreasing) in sample size that approaches a limit (either low or high) with increasing sample size. Figure M-2 gives an example of p-median as prototyped in SADA. In this instance, the metric is plotted as a decreasing function of sample size. As the sample size increases, the metric decreases and appears to be approaching an asymptote of about 50,000 (minimized sum of concern weighted distances). This allows the investigator to judge the worth of additional measurement locations. Check and Cover can indicate the relative change in the p-median minimized sum (or p-median metric) as the number of samples increase. As sample size increases, the effect of each additional sample on the minimized sum of concern weighted distances becomes less pronounced. Depending on cost, somewhere around 8 or 10 might be chosen. An example from Meyer and Brill (1988) may better help show what is occurring. Figure M-3, taken from that reference, depicts a figure of merit (the probability of detecting a ground water plume) versus the number of wells. It appears that after three wells are located, there is little to be gained from sampling additional wells.

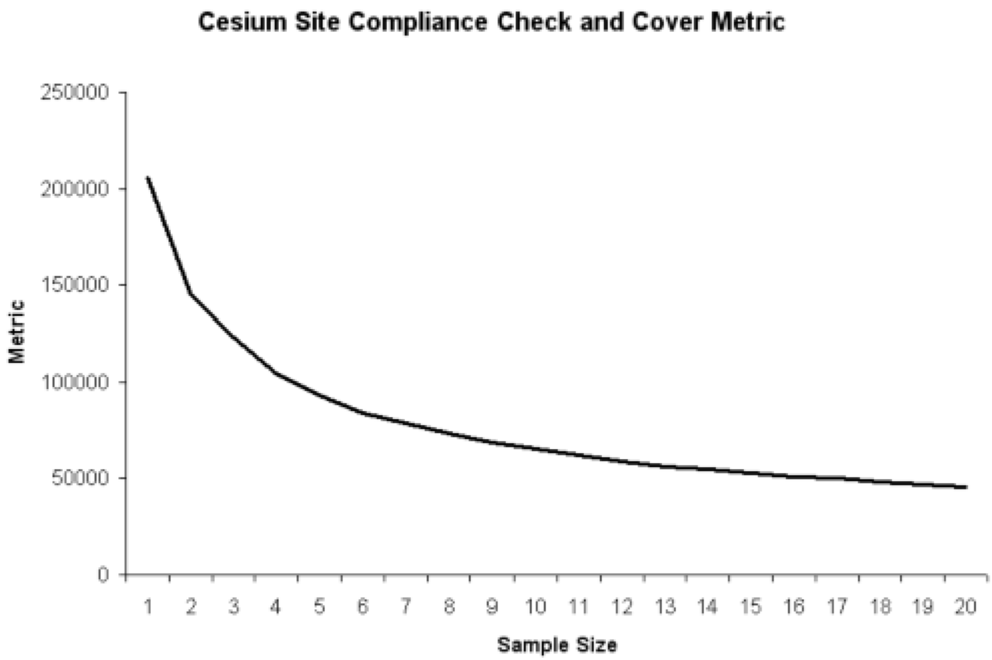

Figure M-2 Example of the Prototype Metric Versus Sample Size in SADA (Stewart 2011)

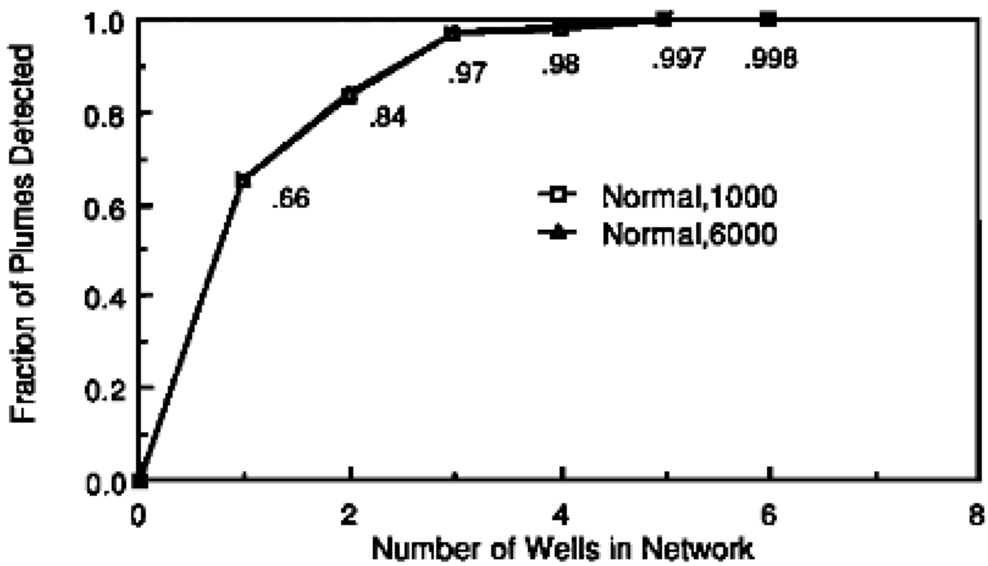

Figure M-3 Probability of Detecting a Ground Water Plume versus Number of Wells (Meyer and Brill 1988)

It should be noted that Visual Sample Plan (VSP) contains a method to identify sampling redundancy. In Section 3.2.10 of the VSP Version 7.0 user's guide (Matzke et al. 2014), the method of Cameron and Hunter (2002) used global kriging weights to identify the relative importance of samples in mapping contaminant plumes and to identify sample locations or wells that could be removed from the sampling schedule. VSP ranks sample locations in terms of their contribution to the plume map through the global kriging weight, and the lowest ranked data location is removed from the data set. The kriging and ranking process is then repeated until the maximum number of samples (wells) is removed from the data set.

Check and Cover sample design has two objectives:

(1) Determine how to use qualitative expert knowledge to strike a balance between taking samples in areas that are highly suspected of contamination (areas of concern in Figure M-4) and those areas that might not be contaminated but nonetheless require some sort of quantitative evidence of this fact early in the characterization phase.

(2) Determine how to account for the level of confidence (reliance factor in Figure M-5) in the prior knowledge.

Check and Cover sample design is implemented within the Develop a New Sample Design Interview (Stewart et al. 2009). The steps that appear for Check and Cover under this interview depend on the data or model that has been selected. If the user has some actual data and would like p-median to factor in determining the arrangement of new locations, then the user is met with a See the Data step. This step allows users to choose the data they wish to use.

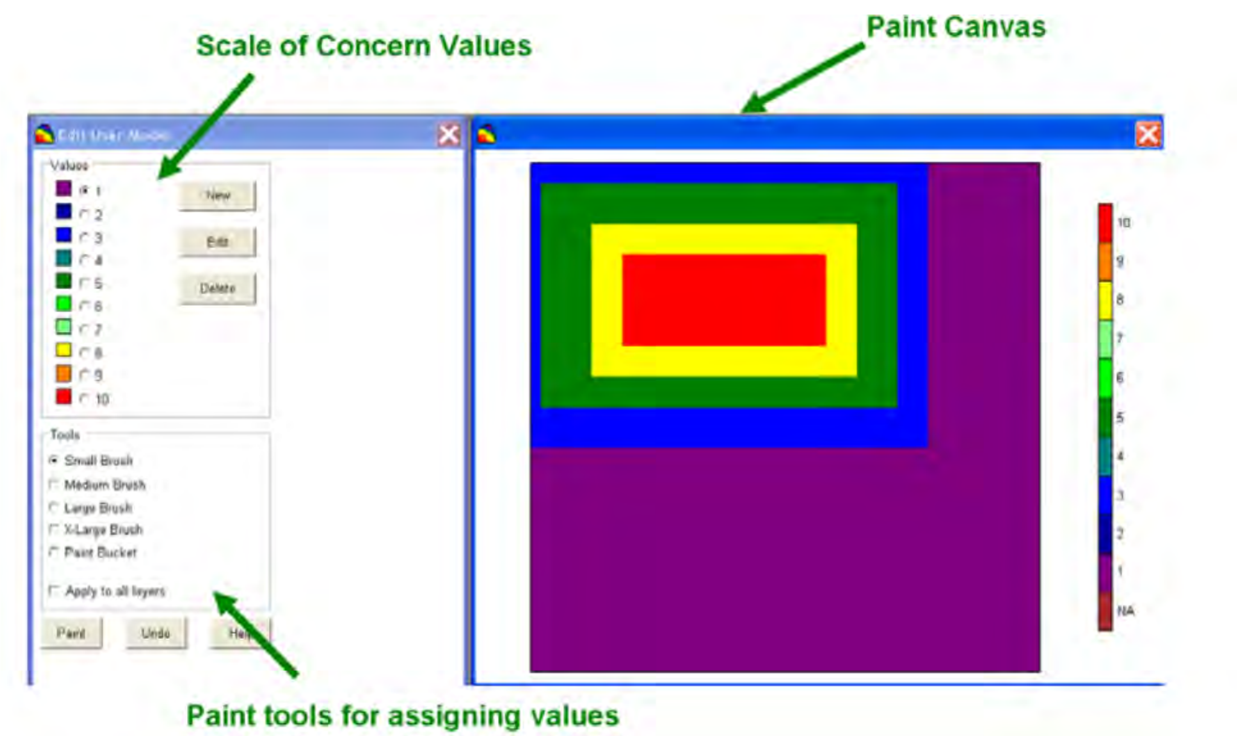

Figure M-4 Users "Paint" Numerical Values into the Model

If the user has no data to consider, then a prior concern model is developed (Figure M-5). The map of prior concern can be "painted" on the map of the site, using a color code to indicate the degree of concern from low (1) to high (10). Figure M-5 shows the Check and Cover parameters within the SADA graphical user interface.

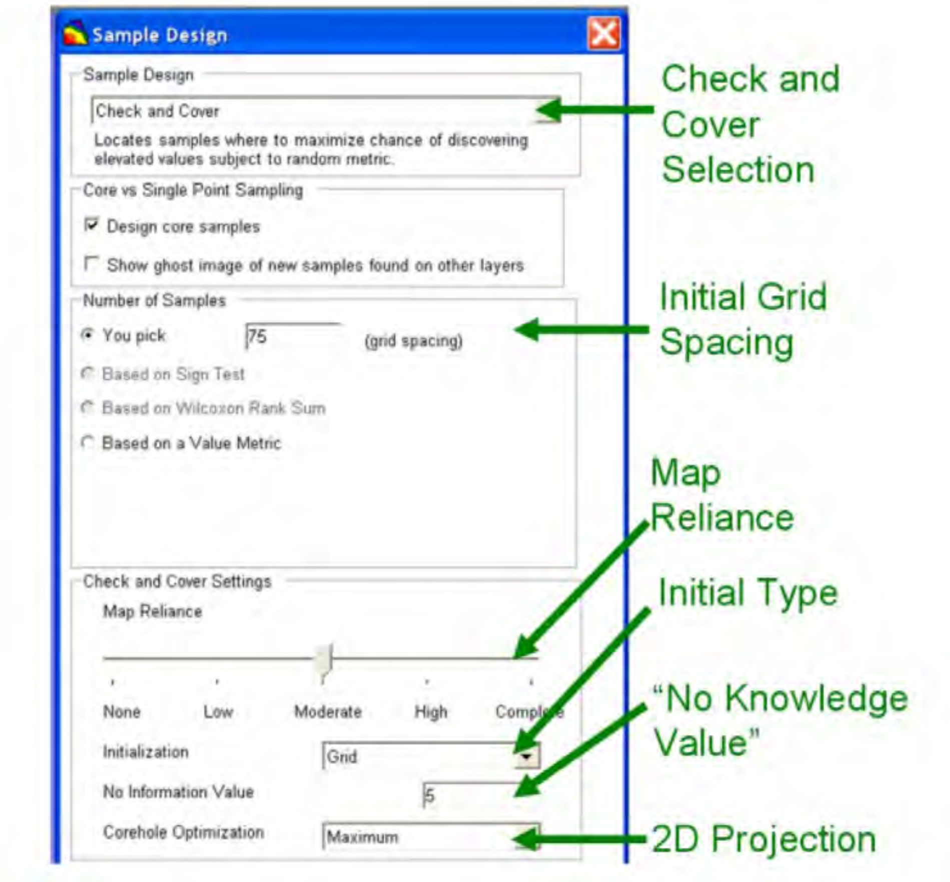

Figure M-5 Check and Cover Parameters within the SADA Graphical User Interface

Show the Results executes Check and Cover, producing the sample design in the results window (Figure M-6). The calculated[2] sample locations are shown as the gray triangles.

2 The routine CalculatePMedianSampleDesign is based on existing p-median code derived from the method for solving the planar p-median problem by Ostresh (1978). The original code was provided during personal correspondence between Robert Stewart and Dr. Bruce Ralston as part of the SADA project in 2009.

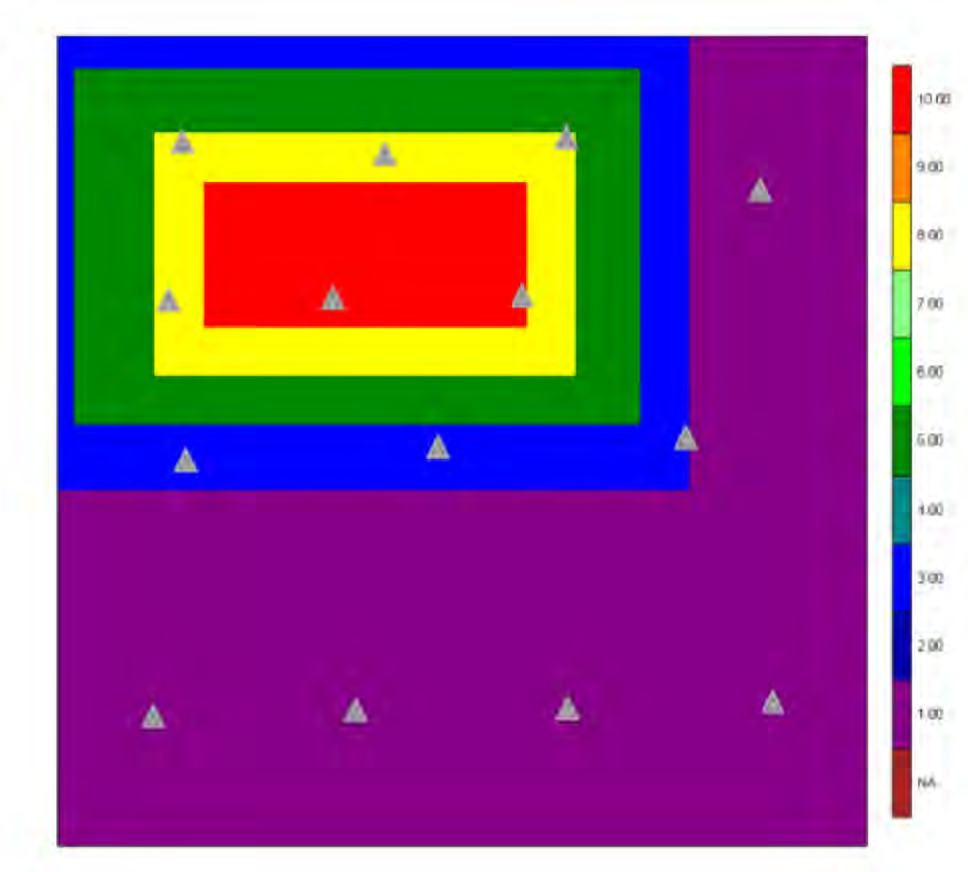

Figure M-6 Example Check and Cover Design

The Sample Design dialog includes the Map Reliance factor. Under Check and Cover, a triangular grid is used as the initial guess. A triangular grid is created by offsetting every other row of a regular grid by half the grid spacing. The effect is to create a triangular pattern in the sampling design. If there are no variations in concern levels, p-median should adjust this initial guess only to spatially balance samples within the site based on site boundaries. If concern levels do vary, p-median moves away from a triangular grid into a more clustered or biased design. Figure M-7 demonstrates the effect of the map reliance factor on an initial guess. Notice how the P-median values tend to provide a regular triangular distribution under the zero reliance (know-nothing) state. On the other end of the spectrum (reliance factor = 1), the design tends to provide preferential sampling balanced by the spatial distribution of concern. This movement by the sample locations reflects the relative change in the concern when adjusted by the reliance factor. For the “None” reliance factor case, the median finds no real improvement in the minimization other than adjustments related to the location of site boundaries. The “Complete” reliance factor case places a premium on the level of concern in the northern portion of the site. P-median responds by moving more samples into that area to minimize the sum.

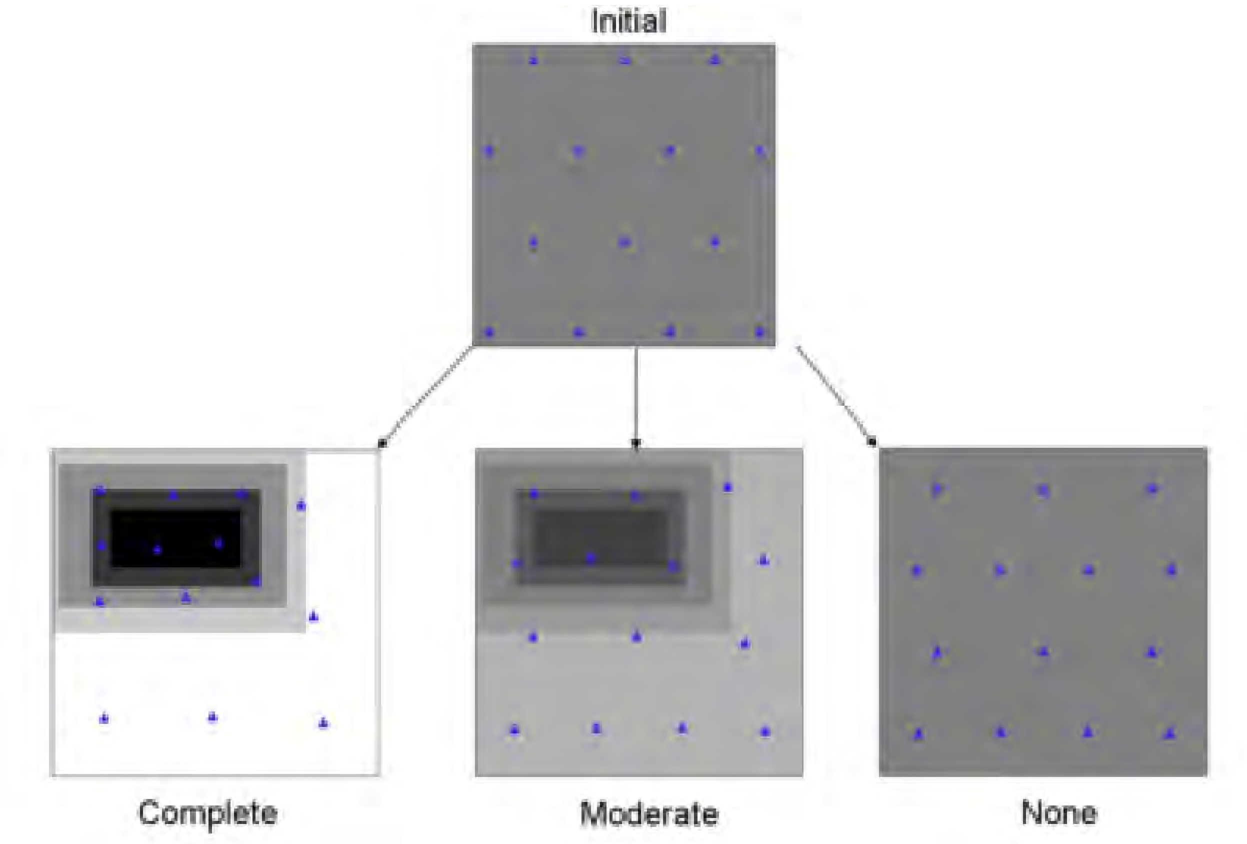

Figure M-7 Map Reliance Factor Effect on Initial Concern Estimate in Figure M-4

Kriging is smoother (less variable) than reality. Everything is related to everything else, but near things are more related than distant things. Interpolated surfaces are usually less variable than the real phenomenon. Interpolations produce a value for every location in the study area, but that one value may not have all the information needed to make good decisions. Simulation methods and techniques generate many interpolated surfaces, all of which replicate the spatial characteristics found in the sample data. These simulated surfaces can be used to construct a distribution of values for each location. These distributions can be used to make more informed decisions under uncertainty (ESRI 2022) and allow analysts to make decisions.

The kriging variance has been used as a model of uncertainty about interpolated values. Under the assumption of normality, the kriging estimate is the mean and the kriging variance is the variance of a normal distribution assigned to each location. A fundamental issue with using the kriging variance this way is that the kriging variance does not involve the actual value of any sample point, but only the distance between values. The result is that variance is only a function of the spatial distribution of sample points and not their values (Goovaerts 1997; Deutsch and Journel 1992). It can happen that while samples collected close together may demonstrate widely different concentration values, estimates in that area will have low kriging variances. Confidence in the true value can be overestimated. On the other hand, geostatistical simulation permits the empirical development of a complementary cumulative distribution function (i.e., probability of exceedance) at each point by creating equiprobable realizations of the random function (Goovaerts 1997) based on actual values. On the left side, Figure M-8 shows example data from the user's guide for SADA Version 5.0 (Stewart et al. 2009) and, on the right side, interpolation of the same. Three geostatistical realizations were generated using the sequential simulation algorithm described in detail in Goovaerts (1997,

p. 377), as shown in Figure M-9. These figures illustrate the smoothing effect of interpolation versus the roughness of individual simulations.

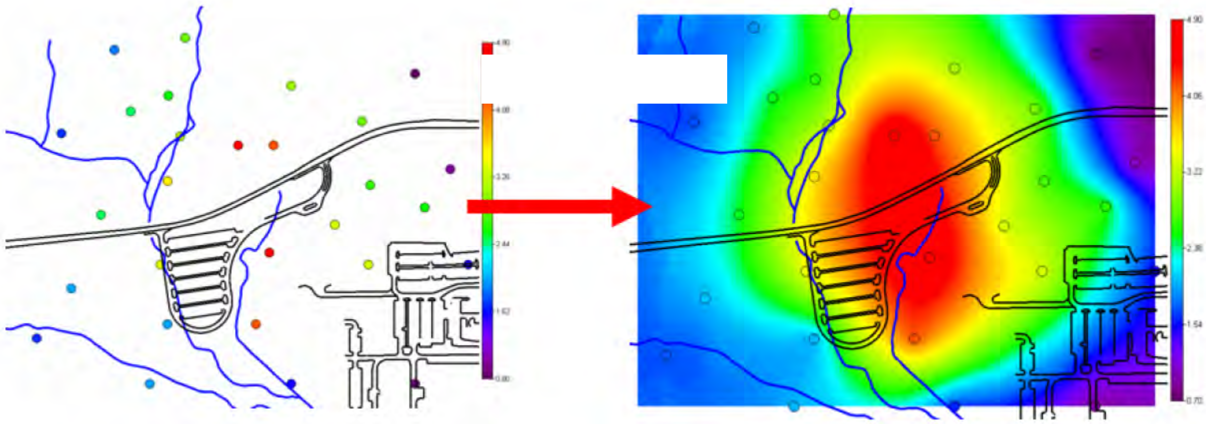

Figure M-8 Example Data (left) and Interpolation of the Same (right) from SADA User's Guide Version 5.0 (Stewart et al. 2009, p. 267)

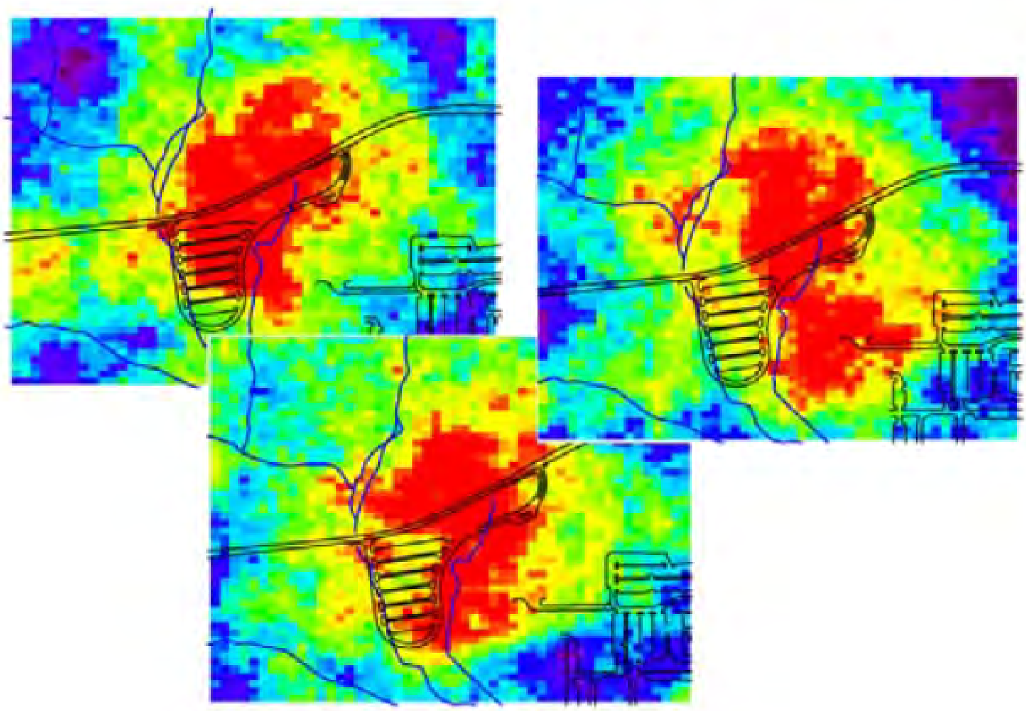

Figure M-9 Three Realizations of a Random Function Simulation Using the Data in Figure M-2 (Stewart et al. 2009, p. 268)

Tools such as geostatistical simulation provide a more rigorous assessment of uncertainty than kriging and greater capabilities in characterizing spatial processes. vKey advances include uncertainty assessment across different spatial scales and methods for integrating various kinds of information (e.g., field and laboratory data) under a single model (Goovaerts 1997). These abilities represent a substantial opportunity for investigators to develop, evolve, and use the conceptual site model as envisioned under Triad.

In Chapter 6 of the dissertation, a hypothetical, radiologically contaminated site (see Figure M-10) is used to demonstrate the prototypes for GEM and for Check and Cover implemented in SADA Version 5.0. The site, referred to as “Cesium Site,” engaged in production activities that led to cesium (Cs)-137 contamination in the subsurface; investigators are interested in determining what (if any) remedial activities might be necessary to bring the site into compliance under the GEM framework’s RLR. The Cesium Site is a 250-foot by 250-foot span of property originally occupied by two buildings and two storage tanks on the northern half of the property. The facility has ceased operations and both the buildings and tanks have been decommissioned (removed).

Under RLR, decision-makers will evaluate a finite set of positions defined by a three-dimensional (3D) grid system. The GEM spatial resolution grid system is formed by overlaying the site in 3D space with a 3D grid specified with origin (x0, y0, z0) and grid cell size (Δx, Δy, Δz). The GEM grid size used was 5′ x 5′ x 1′.

A utility program (SIMSAMPLE, not currently publicly available) was created to emulate data collection from the synthetic model in two ways: laboratory and field measurements. For laboratory measurements, SIMSAMPLE returns the exact value from the true volume. There are no simulated measurement errors in this process. For field measurements, the behavior of particular field sampling technology called a high purity germanium (HPGe) spectrometer is simulated.

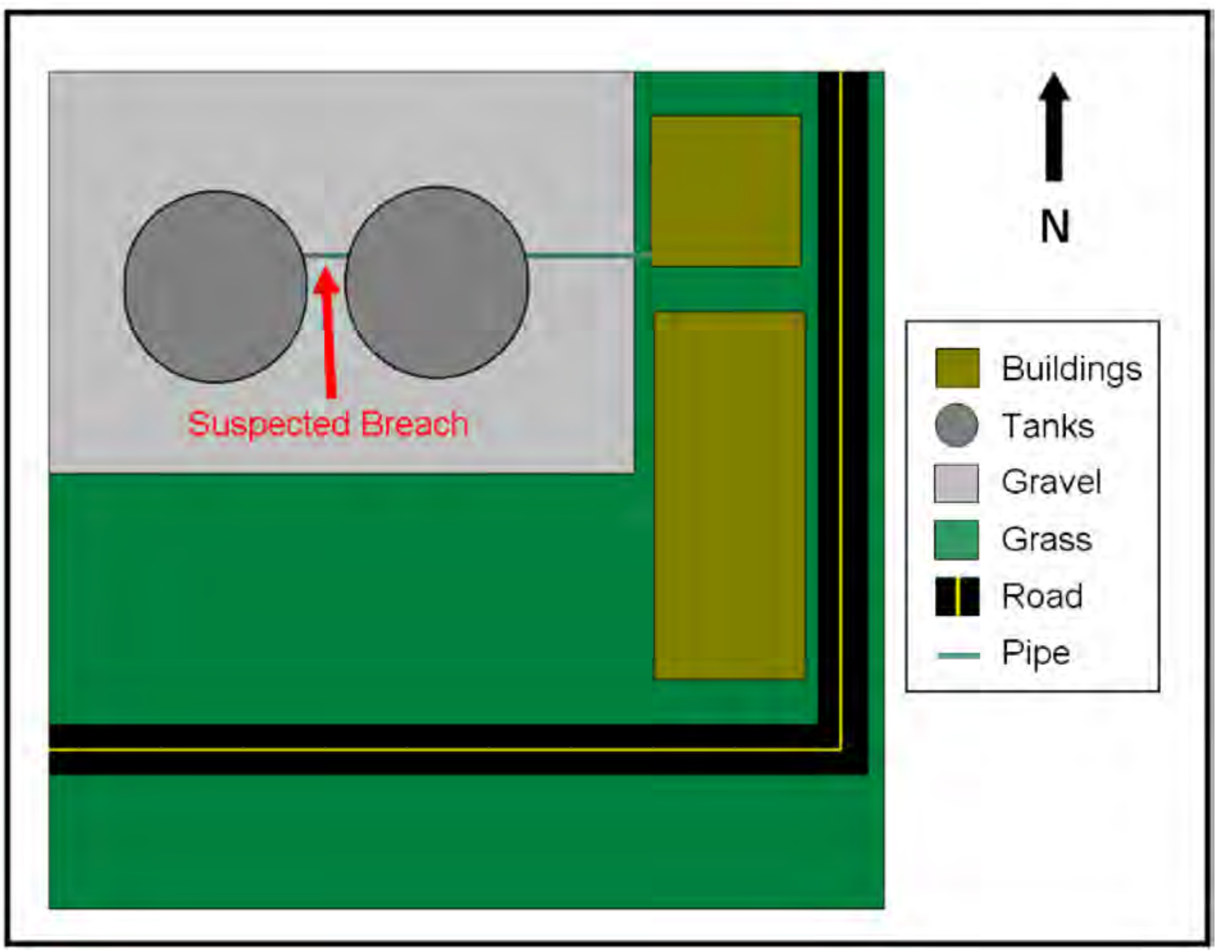

Figure M-10 Hypothetical Site with Cs-137 Contamination

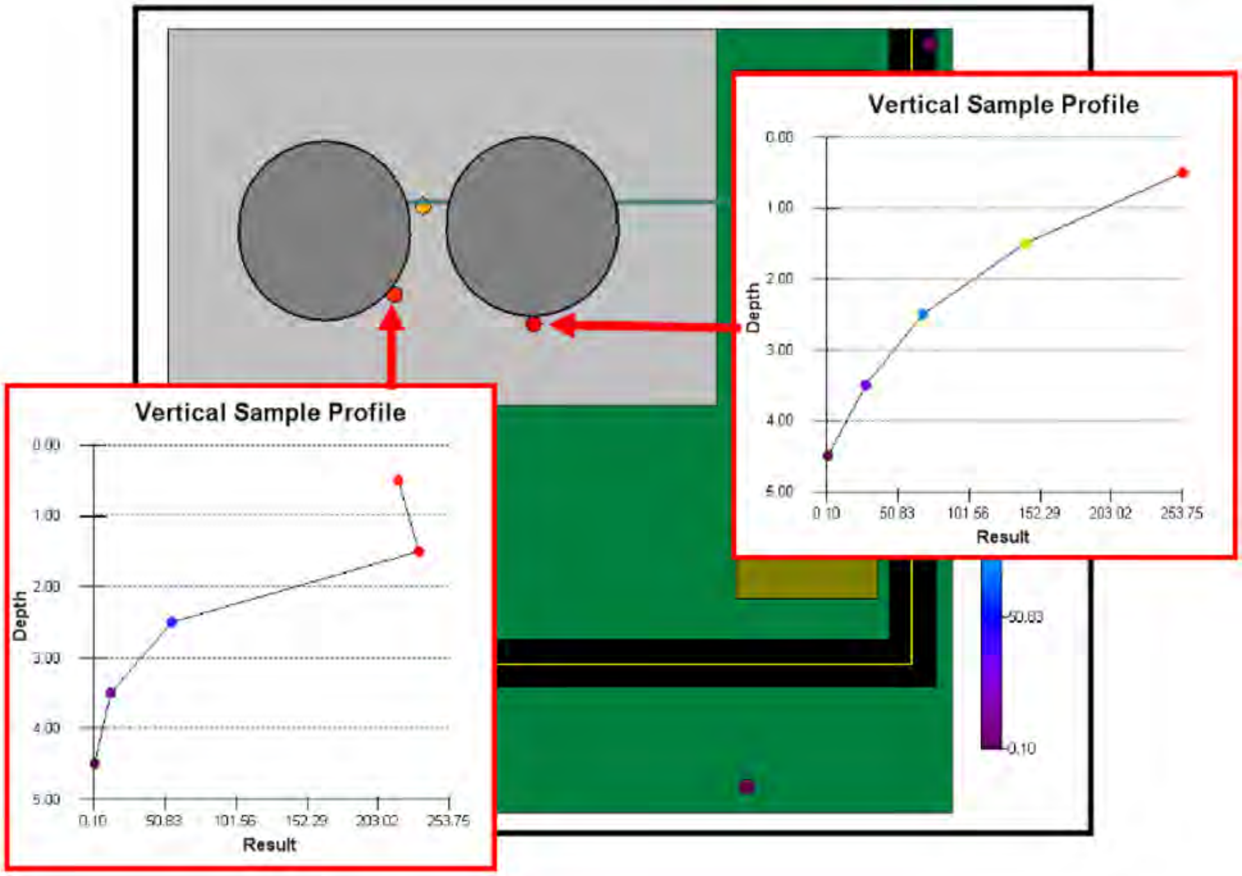

Figure M-11 Vertical Profiles for Scoping Survey Results of Hypothetical Site with Cs-137 Contamination

Scoping results (Figures M-11 and M-12) indicate that a reasonable depth for the site investigation is 5 feet, since even the most contaminated cores reach near zero values at that depth. A number of the core results indicate high levels of Cs-137 at depth. Hence, a characterization is required to determine the extent and exposure risk of the contamination.

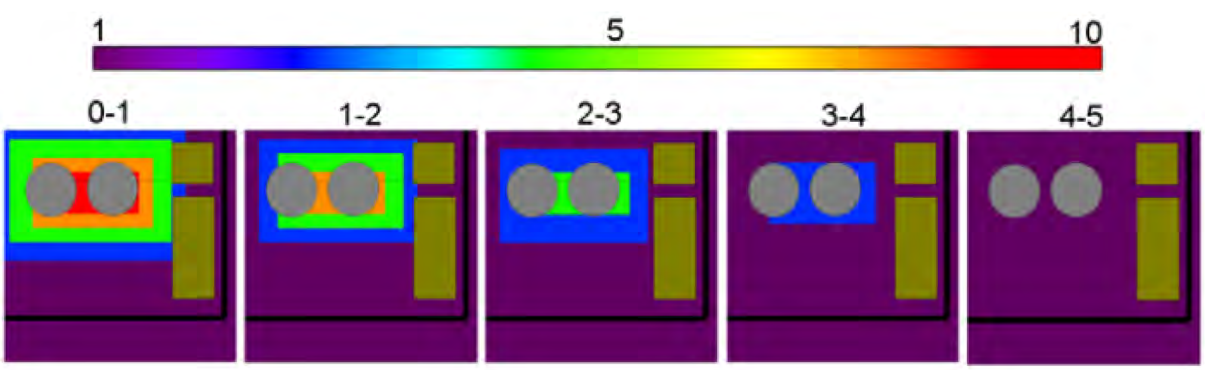

Figure M-12 Prior Estimate of Contamination Concern Model for Cs-137 Contamination Shown Layer by Layer (1 foot intervals from 0 to 5 feet)

The Check and Cover sample design was used to locate the first round of characterization cores.

Investigators agreed to a complete level of confidence in the prior knowledge and decided to project from 3D to two dimensions using the vertical average. To determine the sample size, investigators relied on SADA's Based on A Value Metric option to calculate the minimized p-median values for a range of grid spacings. Figure M-13 shows the results.

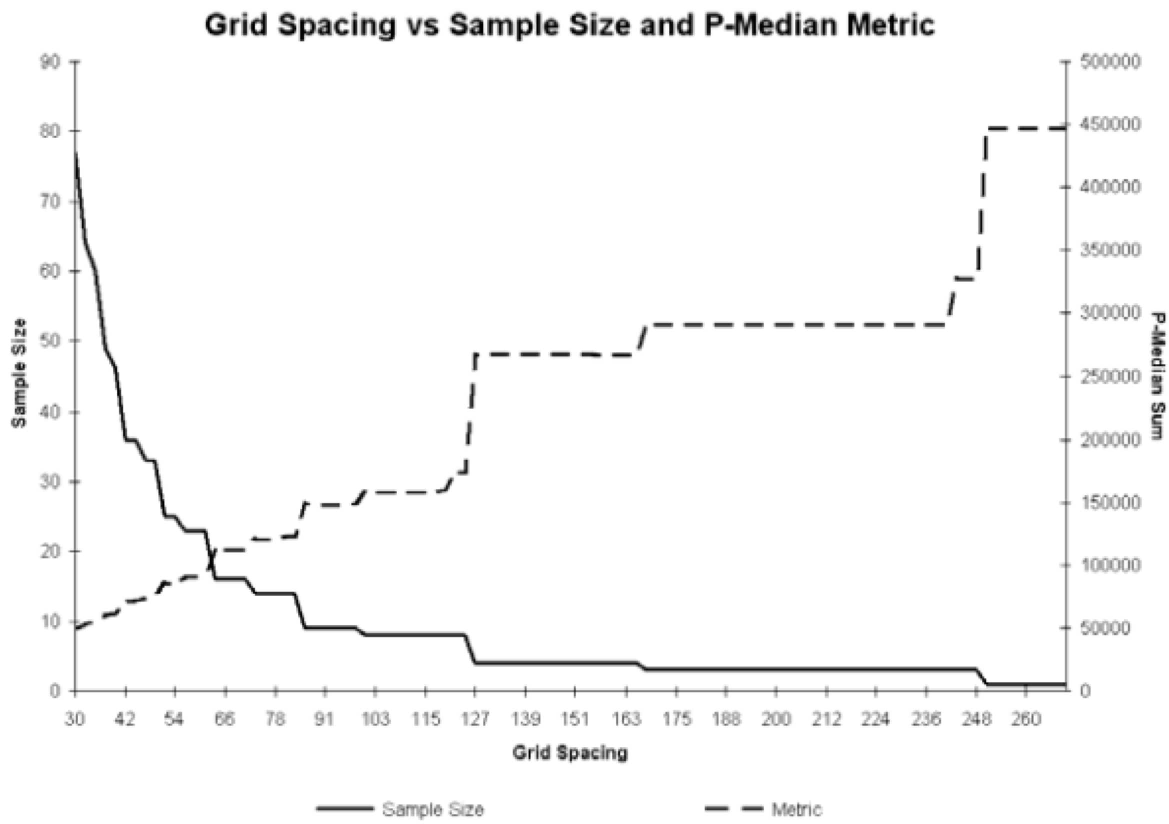

Figure M-13 Grid Spacing versus Sample Size and p-Median Values

Notice that no change in value occurs in several areas along both the sample size line and the metric line. For certain spacing size changes, there is not a corresponding change in the number of samples due. Jumps in sample size occur when the grid spacing allows another line of samples within the survey unit. Plotting the sample size against the p-median metric yields the graph shown in Figure M-14.

Observing that the p-median metric results behave asymptotically and that a sample size of only 9 samples produces 75 percent of the p-median metric reduction at 77 samples, a spacing of 100 feet (9 samples) was selected to begin characterization.

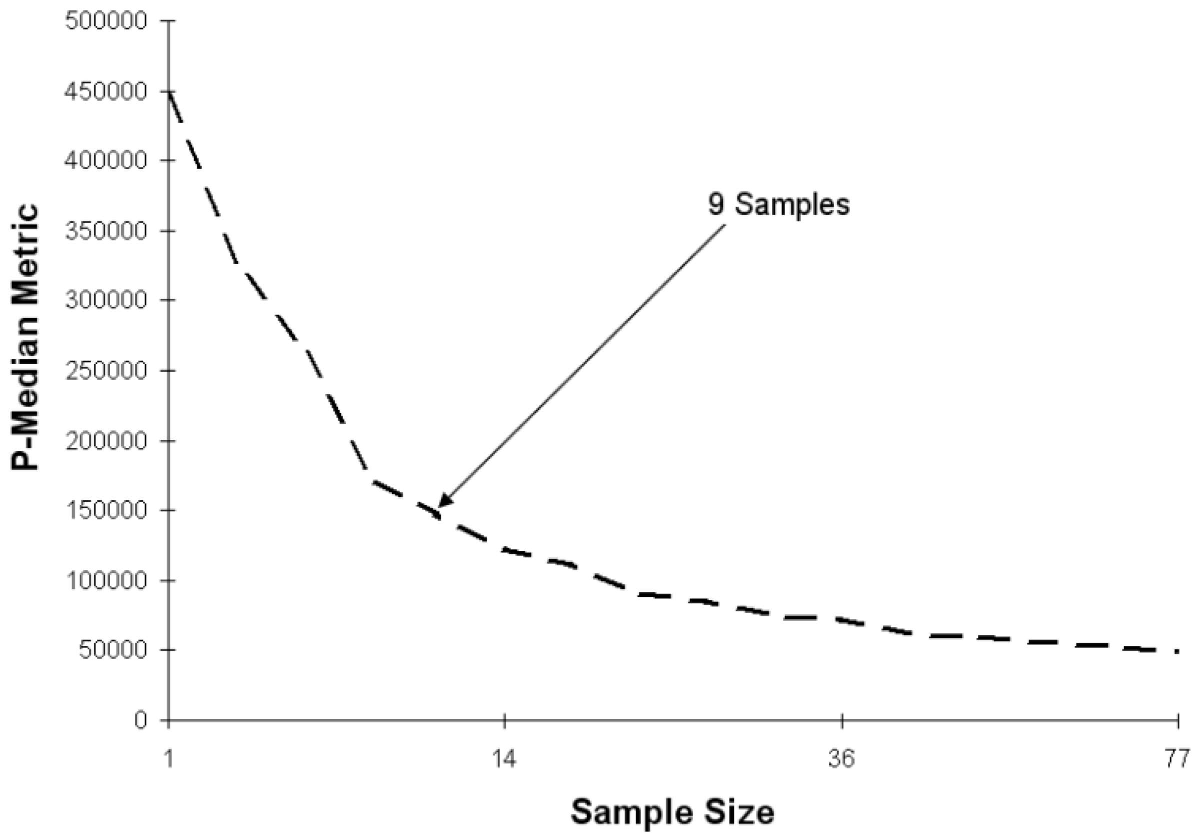

Figure M-14 Number of Samples (for Grid Design) and p-Median Metric

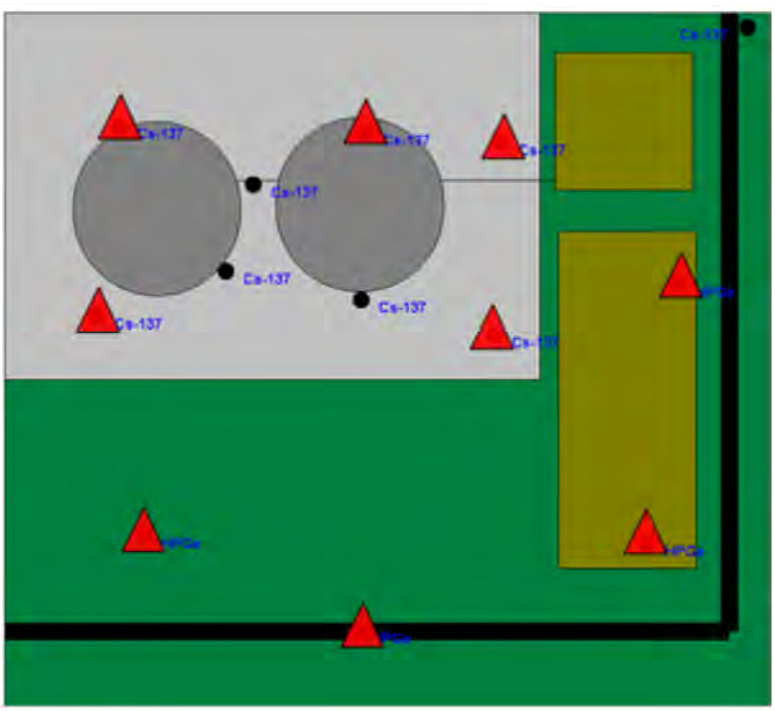

Figure M-15 Check and Cover Places Nine Core Locations (Red Triangles) Based on the Estimated Prior Concern Model

For this hypothetical example, investigators are concerned about an external exposure scenario. Based on the methods in Eckerman and Ryman (1993), DCGL calculations for a set of 3D subsurface exposure units were calculated under an external exposure scenario.[3]

Table M-2 External Exposure Limits (pCi/g) for Nine Exposure Unit Geometry/Volumes

Exposure Unit Geometry	Exposure Unit Volume (cubic feet)	DCGL
5 x 5 x 1	25	118.7
5 x 5 x 2	50	112.7
5 x 5 x 3	75	112.5
15 x 15 x 1	225	43.1
15 x 15 x 2	450	41.6
15 x 15 x 3	675	41.6
25 x 25 x 1	625	33.4

Choosing the simulation model under the Select Simulation Method is the final step before pressing Assess Current Compliance. SADA produces the following results, indicating that the Cesium Site fails the SCSM test for the RLR. The SCSM model also produces maps of failure by exposure unit class (volume). Figure M-16 shows the compliance failures for surface volumes.

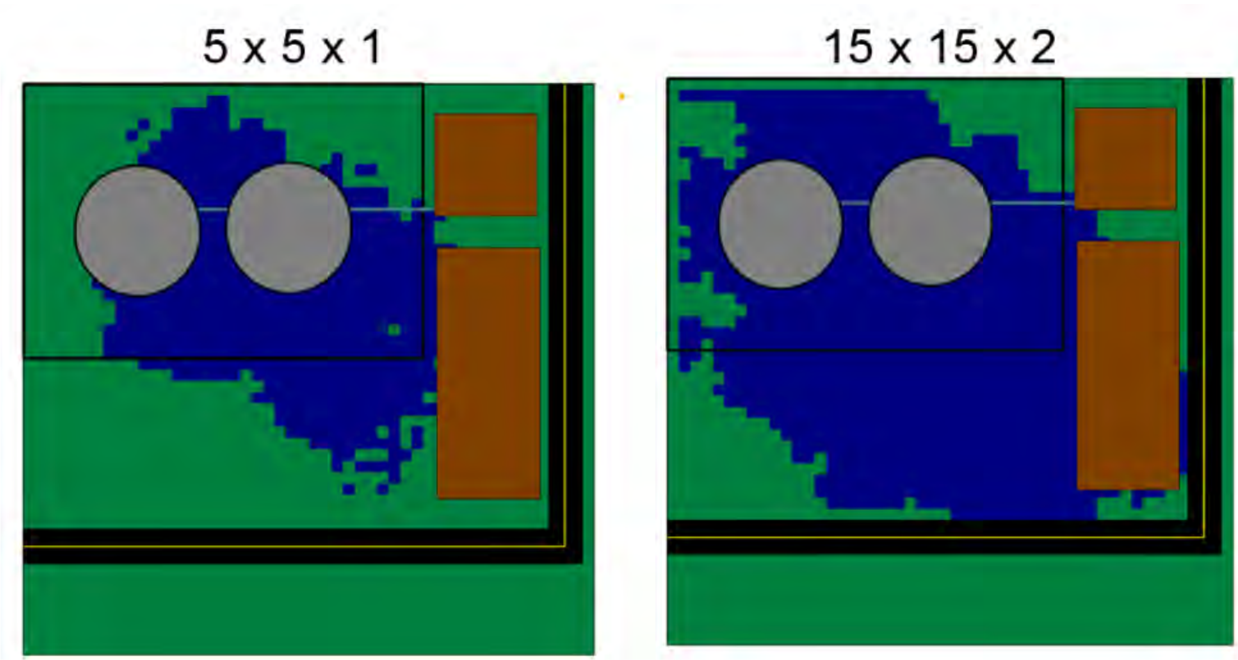

Figure M-16 Location of Compliance Failures for 25 and 450 Cubic Foot Exposure Units

Given the cost of remediating this volume, investigators wonder whether careful selection of a few more cores might decrease the remedial volume required at this high confidence level. MrsDM was applied to determine what cores (if any), if correctly estimated, might lead to a

[3] Values were provided through personal correspondence of Robert Stewart with Dr. Keith Eckerman in 2010.

smaller remedial volume. Investigators create a set of 10 candidate locations using the Adaptive Fill design, from which to choose the best five. Adaptive Fill places new candidate samples in the largest spatial data gaps (Stewart et al. 2009). Figure M-17 shows these candidate locations (at left). Investigators decide to select only the three highest performing core holes in reducing remediation volume (#10, #1, and #3). Laboratory data at these locations are collected, and the simulation model is updated again.

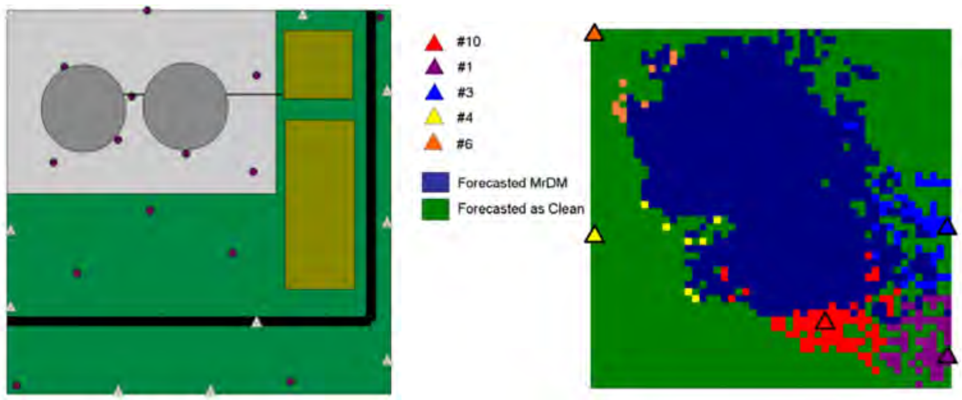

Figure M-17 Ten Adaptive Fill Core Locations (left, triangles); Five Best for Reducing Remediation Volume (right, see legend)

For the Cesium Site, the SCSM model was rerun with the actual remedial design in place. All exposure unit instances at all locations now pass the RLR.

Applying the Check and Cover and the GEM framework to the Cesium Site demonstrates how the methods can be used to place geospatial decision support at the center of the compliance process. In this example, the phases of investigation were used to build a geostatistical simulation model, assess compliance using the RLR and SCSM, and determine where to remediate (MrDM) and take additional samples (MrsDM). MrsDM indicates where additional core hole sampling might improve understanding of the spatial distribution of a contaminant and result in a smaller MrDM remedial design. In this approach, the investigator provides a set of candidate corehole locations. MrsDM then simulates the collection of data at those coreholes by assigning the median simulated value from nearest node in the simulation set. These simulated values are then added to the geostatistical model as if they were actual data and MrDM is rerun. The borehole location that represents the smallest reduction in the sample design in its local area is eliminated, and the process repeats until the specified number of requested coreholes is reached.

M.2 References

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