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RADIOLOGICAL SURVEY AND DOSE MODELING OF THE SUBSURFACE TO SUPPORT LICENSE TERMINATION

DRAFT FOR COMMENT

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) regulations on decommissioning criteria (10 CFR Part 20, Subpart E) for license termination are performance-based and can be as site-specific as necessary for a licensee to demonstrate that the residual radioactivity remaining at their site is within the requirements for the type of termination (unrestricted or restricted release) being requested by the licensee. To support both the licensees and staff, the NRC has developed a series of NUREGs for licensees to develop, and staff to evaluate, the decommissioning plans, license termination plans, and final license termination requests. The core document for the surveys to identify and support the amount of residual radioactivity present at a site and the dose consequences of that residual radioactivity is NUREG-1757, "Consolidated Decommissioning Guidance," Volume 2, "Characterization, Survey, and Determination of Radiological Criteria." The consolidated guidance includes both review criteria (e.g., in Chapters 4 and 5 for surveys and dose modeling, respectively) and appendices with potential approaches to the range of site-specific issues that may arise, generally using graded approaches.

The NRC published Revision 2 to NUREG-1757, Volume 2, in July 2022. NUREG-1757, Volume 2, Rev. 2, incorporated lessons learned and best practices from decommissioning since the last revision. Comments received on NUREG-1757, Volume 2, Rev. 2, included the need for additional guidance on subsurface surveys and associated dose modeling to support development of cleanup levels or derived concentration guideline levels (DCGLs). Two subsurface workshops were held in July 2021 and May 2022 to explore technical issues associated with subsurface investigations. Workshop findings and other information were incorporated into the final guidance document.

Since publication of the NUREG revision, staff have been developing more detailed guidance on subsurface investigations and related technical issues to increase transparency and efficiency in the NRC's license termination review process. For example, the NRC contracted with SC&A to develop a technical white paper "Guidance on Surveys for Subsurface Radiological Contaminants" which was completed in September 2022. This interim staff guidance (ISG) supplements the subsurface guidance in NUREG-1757, Volume 2, Rev. 2, Appendix G and Appendix J, using information from the SC&A technical white paper, information developed by NRC's contractor, Oak Ridge Associated Universities, and the NRC staff's own independent work. The ISG contains no substantive changes to the review criteria in the main chapters of NUREG-1757, Volume 2, Rev. 2.

The ISG focuses on surveys of open surfaces in the subsurface, including open excavations, basement substructures, and materials planned for reuse. The interim guidance addresses the following topics (see Table ES.1 for a more detailed listing):

- Application of the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) to open surfaces found in the subsurface (e.g., open excavations, basement substructures, and materials planned for reuse) prior to backfill.
- Guidance on subsurface survey unit classification, survey unit size, sample density, depth of samples, and statistical tests to demonstrate compliance with release criteria.
- Guidance on instrumentation and survey approaches used by NRC licensees for hard to access locations.

- Dose modeling considerations for buried materials including use of RESRAD-ONSITE to model residual radioactivity released from basement substructures located above and below the water table.
- Additional guidance on the need to obtain site-specific information to support selection of distribution coefficients in dose modeling, and methods to obtain that additional support.
- Additional guidance on assessment of risk from existing groundwater contamination.
- Additional guidance on groundwater monitoring and modeling considerations to support demonstration of compliance with release criteria and license termination.

The ISG is expected to increase consistency in licensee submittals and staff reviews and represents the NRC's commitment to addressing stakeholder needs including consideration of modern approaches to demonstrating compliance with radiological criteria for license termination. This document is being issued for public comment. Comments received on the draft document will be addressed in a comment response document, and a final guidance document will be issued. The final guidance document will be incorporated into future Revision 3 of NUREG-1757, Volume 2.

Table ES.1 Summary Table for ISG

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
Subsurface Investigations	Complexity of Sampling	Section 1 and Appendix A	Append-ix (App) G.3	• Given the relative inaccessibility of the subsurface and inability to scan the subsurface without excavating material, subsurface surveys are complex, and sampling can be resource intensive. Optimization of subsurface surveys is needed to help focus expenditure of limited resources. • If significant quantities of subsurface residual radioactivity are present from previous burials, spills, leaks, and contamination of the subsurface based on the historical site assessment and other sources of information, then the subsurface interim staff guidance (ISG) should be followed. • Federal guidance similar to MARSSIM for subsurface investigations is currently unavailable. • Limited guidance on surveys of open surfaces in the subsurface is provided in NUREG-1757, Volume 2, Rev. 2. • Comments received on draft NUREG-1757, Volume 2, Rev. 2 were considered in finalizing the guidance in 2022. Additional work is being performed to address remaining comments in this ISG and in future staff guidance. • Two subsurface investigations workshops were held in 2021 and 2022. Workshop summaries and video can be found at the following web site: https://www.nrc.gov/waste/decommissioning/whats-new.html

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
				• NUREG/CR-7021 provides a decision framework and tools when subsurface residual radioactivity is present. • NUREG/CR-7021 is being updated considering advances in science and updates to the literature. • Visual Sample Plan (VSP) is being updated considering recommendations in SC&A (2022); Pacific Northwest National Laboratory (PNNL 2022); and Stewart (2011) among other documents.
Surveys of open excavations, substructures and materials planned for reuse	MARSSIM Applicability	Section 2.1	N/A and App G.3	• MARSSIM (and related guidance) principles can be extended to open excavations and the surfaces of substructures that will be backfilled. • New terms and concepts, such as a subsurface survey unit (SSU), are introduced for subsurface final status surveys.
	Categorization and Classification	Section 2.2	App G.3	• Real property is categorized as non-impacted or impacted by site operations; only property that is impacted is subject to a final status survey (FSS). • MARSSIM guidance is being followed for classification—property can be divided into Class 1, Class 2, and Class 3 SSUs.
	Survey unit size	Section 2.3	N/A and App G.3	• The ISG adopts MARSSIM's graded approach to limit the size of SSUs based in part on risk-significance of the SSU (i.e., the risk is based on how close residual radioactivity is to cleanup levels or derived concentration guideline levels [DCGLs]).

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
				• Backfilled substructures should be treated as land for the purpose of survey unit class and size. • SSU size is based on MARSSIM class and associated exposure scenarios (e.g., 2000 and 10,000 m^2 for Class 1 and 2 areas, respectively, based on resident/agriculture scenarios and pathways). MARSSIM inherently considers risk when determining sample/measurement and scan density (i.e., relatively high number of samples/measurements and relatively high scan density when expected concentrations approach DCGLs). • Exposure scenarios for buried or subsurface residual radioactivity include in situ groundwater leaching and potential redistribution of residual radioactivity at the surface due to human activity (e.g., basement excavation, construction project, well drilling). The SSU unit size should be tied to the exposure scenario and potential redistribution of material at the surface.
	Analytical Approach	Section 2.4	N/A, App A and App G	• MARSSIM and related statistical guidance (e.g., EPA 2015) is applied to SSUs. • MARSSIM Scenario A and Scenario B can be used in SSUs when the traditional approach is sufficient; a modified Scenario B approach (B’) is described for materials targeted as backfill.

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
				• Potential statistical tests include use of Wilcoxon Rank Sum and Sign Test (Scenario A and B) or Wilcoxon-Mann-Whitney and t-test (Scenario B'). • SSU compliance strategies also include 95th upper confidence limit (UCL) of the mean, when hypothesis testing is not required, and presence/absence when compliance includes hard-to-detect radionuclides or not to exceed criteria. • Scanning coverage can be limited in SSU due to safety and other physical access issues; the ISG presents alternatives to scanning (e.g., composite sampling, and two-stage sampling).
	Number of Samples	Section 2.5	N/A, App A and App G.3	• Methods are described for estimating how many samples or direct measurements are required to adequately characterize a subsurface area. • The traditional MARSSIM approach is presented for most SSUs, although alternative methods are presented for testing materials targeted as backfill or when estimating mean concentrations.
	Scanning and Direct Measurement	Section 2.6	N/A and App G.3	• The degree of scanning (i.e., coverage) is described, following the MARSSIM approach when possible; the formula for Class 2 SSUs is also presented per Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME) (supplement to MARSSIM). • Potential approaches for scanning embedded piping, boreholes, and hard-to-reach surfaces are discussed.

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
				• Reuse and borrow material should also be scanned to ensure unacceptable residual activity is not introduced into the SSU; methods and the degree of scanning are presented based on the assigned classification. • In situ gamma spectrometry can be used as a substitute for traditional “walk-over” scanning surveys for confined/dangerous spaces or difficult terrains when the licensee demonstrates viability. • In situ gamma spectrometry tends to average out the radioactivity over a large field of view (FOV) and that should be a consideration in survey design when elevated areas are a concern. Collimation is often used with in situ instrumentation. • Taking in situ scans to achieve 100 percent scan coverage will result in overlapping circles representing the FOV of individual scans. The approach can lead to significant overlap and redundancy in the measurements. Shorter count times can be applied to areas that are “scanned” via in situ gamma spectrometry versus longer count times where measurements are taken at sample locations. • A wide range of instruments are described including traditional hand-held alpha/beta scanners (e.g., plastic scintillators), gamma scanners (e.g., NaI detector), and bulk scanners (e.g., conveyor systems).

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
	Sampling Subsurface Media	Section 2.7	N/A	• Various sampling strategies are available to aid with the placement of discrete SSU sample/measurement locations. • Statistical sampling strategies are described as they relate to the sampling goal (e.g., hypothesis testing or elevated area assessment). • Sample depth recommendations are made for soils/substructures, materials targeted for backfill, and miscellaneous materials; sample depth decisions should balance DCGL considerations (i.e., actual expected depth of residual radioactivity used in modeling), regulatory requirements, and the depth of contamination from characterization surveys. • Other considerations include the possibility that contamination levels can vary with depth, in situ gamma spectrometry represents an average across depth and area and will not identify non-gamma emitters. • Direct measurement (e.g., using a gas proportional detector) applicability is limited to surface contamination. • The number of in situ gamma spectrometry models that need to be constructed will be based on the expected variability of depth of residual radioactivity.
	Consolidated Guidance	Section 2.8	N/A	• Example studies (cases) are presented as guidance for developing FSS data quality

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
				objectives for subsurface/excavation soils (Case 1), a basement substructure (Case 2), and a borrow site (Case 3).
	Overlapping Surveys Remedial Action Status Surveys (RASS) and FSS Surveys	Section 2.9	N/A and App G.7	• RASS of open excavations should be performed to the quality of an FSS for subsurface materials below the excavation. • FSS of soils from the surface down to the excavation bottom can be performed to assess the added risk from slightly contaminated reuse soils. • The licensee should consult with the NRC if there are conflicting results in overlapping FSS/RASS surveys. • Separate DCGLS may be needed for surface/reuse, and/or subsurface residual radioactivity or a conservative approach to DCGL development can be used. • Depth discrete sampling may be needed dependent on the sensitivity of dose to thickness and depth of residual radioactivity.
	Role of Independent Verification	Section 2.10	N/A	• Independent verification/confirmatory surveys are used to evaluate, among other things, a licensee's FSS plans and procedures, instrumentation use and control, data interpretation, implementation methods and effectiveness, and reporting completeness and accuracy. • Common lessons learned are presented to help prevent future problems.

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
Dose Modeling—DCGLs and dose from substructures	Use of RESRAD-ONSITE for reactor basement substructures	Section 3.1 (unsubmerged) and 3.2 (submerged)	App J	• RESRAD-ONSITE’s conceptual model is inconsistent with a source associated with a resistive flow barrier such as a reactor basement or other substructure, which may experience a bathtub effect. • For sources located below the water table (e.g., submerged reactor substructures), the source to well geometry may differ from that assumed in RESRAD-ONSITE. • Simplifications can be made to allow use of RESRAD-ONSITE to derive DCGLs for sources located in the vadose zone (e.g., assume source is closest to the aquifer on the basement floor and the structure is not a barrier to groundwater flow to the aquifer). • For sources associated with substructures located across or below the water table surface, use of the RESRAD-ONSITE non-dispersion model could lead to underestimates of dose due to excessive dilution in the well. The dilution factors should be calculated or checked to ensure that doses are not underestimated. • More sophisticated codes can be used to assess the expected amount of dilution in a well for more realistic flow conditions and source to well geometries to provide support for the use of RESRAD-ONSITE for DCGL development.

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
Risk-Significant Parameters	Challenges with Selection of Deterministic Values for Uncertain Parameters	Section 3.3	App I and Q	• Some risk-significant parameters may have overly broad parameter distributions and/or parameter distributions that are based on sparse or low quality data. • The 25th or 75th percentile values of the parameter distributions from the literature are not always technically defensible or demonstrably conservative. • Additional parameter support may be necessary for especially risk-significant parameters such as K_d. • Various approaches can be used to determine the risk-significance of input parameters including probabilistic and deterministic sensitivity analysis. • Insignificant parameters and pathways contributing less than 10 percent of the release/dose limit considering uncertainty can be eliminated from detailed study and no additional parameter support would be needed. • Approaches for obtaining additional support for K_ds include use of literature values (with a good understanding of the geochemical and other site-specific factors influencing the K_d value), use of lookup tables w/ site-specific information, collection of paired groundwater/soil samples, geochemical modeling, monitoring, or modeling data on plume transport, and finally batch/column experiments.

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
DCGL Development	Need to consider multiple DCGLs for elevated areas or for different strata	Section 3.5 Section 5.1	App G.3, G.4, and G.7 App J	• Typically, exposure scenarios that could bring residual radioactivity to the surface need to be considered when deriving subsurface soil DCGLs. • The cumulative risk from multiple sources of residual radioactivity needs to be considered in demonstrating compliance with release criteria. • Alternatively, an exposure scenario that considers no cover above the subsurface residual radioactivity (i.e., assumes soil cover is removed) and leaching of the subsurface residual radioactivity to groundwater with the depth to water table consistent with the actual configuration of residual radioactivity can also conservatively be considered to reduce the need for modeling more than one exposure scenario. • Licensees should consider the need to develop $DCGL_{EMC}$s for smaller volumes of soil that may be brought to the surface (e.g., well drilling scenario). Given the likelihood and small potential risk, in some cases, licensees have used an effective DCGL to account for multiple potential exposure scenarios and simplify the DCGL development process (e.g., DCGL based on in situ leaching, excavation, and well drilling). • In some cases, rather than develop multiple DCGLs, licensees have used a single DCGL to account for the total thickness of residual radioactivity. In these cases, depth discrete

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
				sampling may be needed if only the surface residual radioactivity or the residual radioactivity at depth is most important to the compliance demonstration (e.g., it may not be acceptable to average higher concentrations with lower concentrations over a large soil thickness if there is vertical heterogeneity).
Assessing Dose from Existing Groundwater Monitoring	Use of RESRAD-ONSITE to calculate groundwater pathway dose conversion factors or PDCFs	Section 4.1	N/A	• RESRAD-ONSITE can be used to calculate pathway dose conversion factors (PDCFs), which are the dose per unit groundwater concentration. • PDCFs can be used to determine the potential dose contributions from existing groundwater contamination. • Biosphere parameters such as drinking water rate, irrigation rate, etc. are important to PDCFs. • Sensitivity analysis can be performed to ensure that the PDCFs are accurately calculated. For example, rapid source depletion can lead to inaccurate PDCFs due to use of an integrated dose with an instantaneous groundwater concentration to calculate the PDCF.
Groundwater Monitoring Data	Methods to Estimate Magnitude and Extent of Groundwater Contamination	Section 4.2	App F	• Monitoring wells may not be optimally located to provide adequate data to estimate potential groundwater dose to demonstrate compliance with radiological criteria for license termination. • Various approaches are available for assessing the dose contributions from existing groundwater contamination including use of monitoring well data

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				trends. If monitoring well data is insufficient for use in estimating potential exposure concentrations, subsurface soil data in the source area can be used to infer aqueous phase concentrations, temporary wells near or below likely identified source areas can be constructed to collect data, or groundwater modeling can be performed to support assessment of the risk from residual radioactivity in groundwater. • The approach taken to estimate the risk from the groundwater pathway should be site dependent, is graded based on site complexity and risk, and justification for the approach should be provided. • Data quality objectives for groundwater sampling should consider the sufficiency of the monitoring well network to collect data to support license termination, including the types of analyses to be performed to measure radioactivity in groundwater and the frequency and location of groundwater sampling.
Leak Detection	Leak Detection Methods	Section 4.3	N/A	• Various methods are available to detect potential leaks that could lead to existing groundwater contamination. • Geophysical methods were discussed at the 2022 NRC-sponsored subsurface workshop ML22136A196 • NUREG-2151 provides additional information on leak detection methods.

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
Decommissioning Impacts on Hydrogeological Conceptual Model (HCM)	Changes in the HCM based on	Section 4.4	N/A	• Dismantling and deconstruction activities may lead to changes in groundwater flow directions and the HCM. • Removal of buildings and roads may lead to changes in runoff and the amount of recharge to the aquifer that should also be considered in dose modeling. • The monitoring well network may not be sufficient to understand changes in groundwater flow directions during deconstruction activities and may need to be augmented. • The impact of changes in the HCM should be considered in demonstrating compliance with license termination rule criteria.
Purpose of Groundwater Monitoring	Basis and Objectives of Groundwater Monitoring	Section 4.5	App F	• Surveys of groundwater are required to understand residual radioactivity levels during facility operation, as well as during decommissioning for licensed and unlicensed material, and for accidental or routine releases. • Surveys are required to determine concentrations and quantities of radioactive material in groundwater to comply with the regulations in 10 CFR Part 20, Subpart E. • The Groundwater Contamination Task Force (GTF) was tasked with investigating leaks of tritium to groundwater at several nuclear power plants and published a report which provides information

Topic	Subtopic	Section of ISG	Section of NUREG-1757, Volume 2, Rev. 2	Key Points
				about applicable regulations related to groundwater monitoring. • The purposes of groundwater monitoring change from operations to decommissioning. • Groundwater monitoring objectives include (i) assessment of risk to workers and members of the public during decommissioning, (ii) support for contaminant flow and transport modeling, (iii) assessment of need for NRC consultation with the EPA under the NRC/EPA memorandum of understanding (MOU), (iv) monitoring changes in flow direction and the HCM due to decommissioning activities, and (v) remedial performance monitoring, as applicable.

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ABBREVIATIONS AND ACRONYMS

ADAMS	Agencywide Document Access and Management System
Ac	Actinium
AEC	Atomic Energy Commission
ALARA	as low as reasonably achievable
Am	Americium
Bq	becquerel
Ci	curie
Co	Cobalt
CCM	contamination concern map
CDE	common data environment
CDF	cumulative distribution function
CLT	central limit theorem
cm	centimeters
CSM	conceptual site model
Cs	Cesium
DandD	Decontamination and Decommissioning (computer code)
DCGL	derived concentration guideline level
DCH	Data Collection Handbook
DL	discrimination level
DP	decommissioning plan
DoD	Department of Defense
DOE	Department of Energy
DQA	data quality assessment
DQO	data quality objective process
DU	decision unit
EMC	elevated measurement comparison
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ERT	electrical resistivity tomography
ESRI	geographic information system company
FIDLER	field instrument for detecting low energy radiation
FOV	field of view
FSS	final status survey
FSSR	final status survey report
FSSP	final status survey plan
GIS	Geographic Information System
GLS	generalized least squares
GMS	Groundwater Modeling System
GPR	ground penetrating radar
GPS	Global Positioning System
GTF	Groundwater Contamination Task Force

H-3	tritium
H_A	alternative hypothesis
H_0	null hypothesis
HCM	hydrogeological conceptual model
HPGe	high-purity germanium (detector)
HSA	historical site assessment
HTD	hard-to-detect
I	iodine
ISG	interim staff guidance
ISGS	in situ gamma spectrometry
ISOC	in situ object counting system
IV	independent verification
K_d	distribution coefficient
LBGR	lower bound of the gray region
LIDAR	light detection and ranging
LISA	local indicator of spatial association
LTP	license termination plan
M&E	material and equipment
MAC	materials acceptable criteria
MARSAME	Multi-Agency Radiation Survey and Assessment of Materials and Equipment
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MB	mass balance
MCL	maximum contaminant level
MDC	minimum detectable concentration
mrem	millirem
MODFLOW	USGS modular finite difference flow model
MOU	memorandum of understanding
MQO	measurement quality objective
MT3DMS	Modular 3D Transport Model Multi-Species
NaI	sodium iodide (detector)
NBS	National Bureau of Standards
NEI	Nuclear Energy Institute
ND	non-dispersion
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NTE	not to exceed (threshold)
OMB	Office of Management and Budget
ORAU	Oak Ridge Associated Universities
PDCF	pathway dose conversion factor
PDP	performance demonstration program
PNNL	Pacific Northwest National Laboratory
ProUCL	EPA statistical software program
PSQ	principle study question
Pu	plutonium
QA	quality assurance
QC	quality control
RAIs	requests for additional information

RASS	remedial action support survey
RESRAD	RESidual RADioactivity (computer code)
ROC	radionuclide of concern
RSCS	Radiation Safety & Control Services
RSSI	radiation survey and site investigation
SADA	Spatial Analysis Decision Assistance (computer code)
SDU	small decision unit
SOF	sum of fractions
SRS	Savannah River Site
SSC	systems, structures, and components
SSU	subsurface survey unit
SU	survey unit
Sv	sievert
Tc	technetium
TDEM	time domain electromagnetics
TEDE	total effective dose equivalent
TRU	transuranic
VSP	Visual Sample Plan
UBGR	upper bound of the gray region
UCL	upper confidence level
USCS	unified soil classification system
USGS	United States Geological Society
UTL	upper tolerance level
VSP	Visual Sample Plan (computer code)
WAC	waste acceptance criteria
WMW	Wilcoxon-Mann-Whitney
WRS	Wilcoxon Rank Sum

1. BACKGROUND AND PURPOSE OF THE GUIDANCE

The U.S. Nuclear Regulatory Commission (NRC) regulations on decommissioning criteria (10 CFR Part 20, Subpart E) for license termination are performance-based and can be as site-specific as necessary for a licensee to demonstrate that the residual radioactivity remaining at their site is within the requirements for the type of termination (unrestricted or restricted release) being requested by the licensee. To support both the licensees and staff, the NRC has developed a series of NUREGs for licensees to develop, and staff to evaluate, the decommissioning plans, license termination plans (LTPs) and final license termination requests. The core guidance document used for surveys to identify and support assessment of the amount of residual radioactivity remaining at a site and the dose consequences associated with that residual radioactivity is NUREG-1757, "Consolidated Decommissioning Guidance," Volume 2, "Characterization, Survey, and Determination of Radiological Criteria." The consolidated guidance includes both review criteria (e.g., in Chapters 4 and 5 for surveys and dose modeling, respectively) and appendices with potential approaches to the range of site-specific issues that may arise, generally using graded approaches.

The NRC is expanding its guidance for subsurface investigations to include such topics as radiological survey and dose modeling to derive cleanup levels for subsurface materials. Federal guidance for radiological surveys during all phases of the radiological survey and site investigation process is found in the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) (NUREG-1575). However, MARSSIM guidance focuses on radiological survey approaches for residual radioactivity found in surficial materials (e.g., around the top 15 cm of soil) and is not appropriate for subsurface soil below around 15-30 cm. NUREG-1757, Volume 2, Rev. 2, provides guidance on radiological surveys of subsurface residual radioactivity in Appendix G, although the information is limited in extent. NUREG-1757, Volume 2, Rev. 2, also provides guidelines in Appendix J on the types of exposure scenarios (e.g., scenarios that could bring residual radioactivity to the surface as well as in situ leaching to groundwater) that should be considered to derive release limits for subsurface residual radioactivity. In response to comments received on draft NUREG-1757, Volume 2, Rev. 2, and due to the complexity of the problem, the NRC indicated that staff would develop interim staff guidance (ISG), which would be incorporated into the next revision of NUREG-1757, Volume 2. This ISG contains no substantive changes to the review criteria in the main chapters of NUREG-1757, Volume 2, Rev. 2.

Final status surveys (FSS) are typically used to confirm that residual radioactivity remaining at the site meets radiological criteria in 10 CFR Part 20, Subpart E, and rely on a combination of sampling (or direct measurement) and scanning to identify elevated areas between sampling locations. When subsurface residual radioactivity is present, the traditional scanning approaches that are effective for identifying elevated areas in surface soil cannot be relied on for subsurface soil and structures. However, in some cases residual radioactivity above release limits needs to be remediated and because of the remediation process, exposed subsurface soils become amendable to scan survey. In other cases, subsurface structures may remain following decommissioning and are available for survey prior to being backfilled. MARSSIM approaches can more easily be extended to these types of problems where subsurface surfaces are readily available for scan survey. Chapter 2 provides a technical basis for survey of exposed surfaces in the subsurface where MARSSIM principles can more easily be extended, including surveys of open excavations following remediation, building substructures, and materials planned for reuse in subsurface voids.

The RESRAD Family of Codes is a set of codes that are commonly used to develop cleanup levels, or derived concentration guidelines levels (DCGLs). RESRAD-ONSITE has been used to develop DCGLs for reactor substructures. While RESRAD-ONSITE considers sources located above, at, or below the water table, the source and well configuration options are limited, and RESRAD-ONSITE does not consider the dose from existing groundwater contamination (not associated with the source). Furthermore, RESRAD-ONSITE has a simplistic saturated zone groundwater model that does not include vertical and horizontal barriers to flow in the aquifer, which may be present when building substructures are present in the saturated zone. Therefore, if RESRAD-ONSITE is used to calculate DCGLs for basement substructures located in the saturated zone, support should be provided to show that the conceptual and mathematical model limitations do not lead to an underestimate in dose from the groundwater pathway. Chapter 3 provides information on dose modeling considerations when developing cleanup levels for basement substructures, which may be located below the water table. Chapter 4 provides guidance on methods to appropriately consider the added dose from existing groundwater contamination, if present. Chapter 4 also provides additional guidance on groundwater monitoring and modeling to support license termination. Chapter 5 provides lessons learned from reviews of decommissioning plans, LTPs, and final status surveys (FSSs) including several case studies. Chapter 6 contains a crosswalk on how information in this ISG will be incorporated in the next revision of NUREG-1757, Volume 2.

Background information on the development of this ISG with more detailed discussion of public comments on NUREG-1757, Volume 2, the results of subsurface workshops, and white papers developed for the NRC are included in Appendix A. Appendix B briefly discusses tools available in various computer codes for data visualization and analysis. Appendix C describes geostatistical methods for subsurface survey data analysis including methods to optimize subsurface sampling.

1.1 When Does a Licensee Need to Worry About Subsurface Surveys

Before using this guidance, the licensee should first determine whether it has the potential for subsurface residual radioactivity that may need to be surveyed and the risk assessed (see NUREG-1757, Volume 2, Appendix G, Section G.3.1). The historical site assessment (HSA) and other site information 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 soil or groundwater 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.

If the survey data indicate that there is significant 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 or remedial action support survey (RASS) typically provides information to help design the survey.

Performing radiological surveys at sites with significant quantities of subsurface residual radioactivity is more complex than surveying surface soil because of the relative inaccessibility of the subsurface regions (e.g., subsurface soil 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 groundwater also presents challenges to subsurface radiological surveys (see NUREG-1757, Volume 2, Revision 2, Appendix F and Chapter 4 of this ISG). Because the MARSSIM methodology relies heavily on scanning to identify elevated areas, 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, "A Subsurface Decision Model for Supporting Environmental Compliance" (NRC 2012) 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 relevant 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 are surrogates to scanning to facilitate better sampling designs and decision-making. For complex decommissioning cases with subsurface residual radioactivity and ground water contamination, it is important for licensees to work with the NRC early in the process to discuss acceptable approaches for demonstrating compliance with radiological criteria for license termination.

1.2 Technical Issues to be Addressed in this Guidance Document Versus in the Second Phase of ISG Development

This report focuses on surveys of open surfaces in the subsurface, including excavations, substructures and materials planned for reuse using MARSSIM principles to the extent practical. Longer-term plans are to update NUREG/CR-7021, "A Subsurface Decision Model for Supporting Environmental Compliance," published in 2012. The update to NUREG/CR-7021 will consider the SC&A White Paper described above, Electric Power Research Institute's (EPRI) "Guidance for Using Geostatistics to Develop Site Final Status Survey Program Plant Decommissioning" (EPRI 2016), PNNL's "Subsurface Radiological Survey Design and Geospatial Analysis Tool Recommendations" (PNNL 2022), Robert Stewart's "Geospatial Based Decision Framework for Extending MARSSIM Principles into the Subsurface" (Stewart 2011), and other technical reports completed since the NUREG was issued in 2012. The updated to NUREG/CR-7021 will provide a complete methodology for optimization of subsurface survey design considering the difficulty in sampling the subsurface, as well as additional worked out examples illustrating the use of tools added to a beta version of Spatial Analysis and Decision Assistance (SADA) to facilitate remedial and compliance phase decision-making (e.g., check and cover, multi-scale remedial decision model, and multi-scale remedial sample decision model from Stewart 2011).

2. SURVEYS OF OPEN EXCAVATIONS, BUILDING SUBSTRUCTURES AND MATERIALS PLANNED FOR REUSE

This chapter provides supplemental guidance for performing a FSS of an open excavation, building substructure, or soils/materials planned for reuse (or borrow) at licensed and unlicensed sites undergoing decommissioning to meet the NRC's release criteria in 10 CFR Part 20, Subpart E. NUREG-1757, Volume 2, Rev. 2, Appendix G and J (NRC 2022) on subsurface surveys and dose modeling are considered a starting point for this supplemental guidance. Information related to the following broad topics is provided:

1. Categorization and classification of subsurface and potential reuse materials,
2. Selection of subsurface survey units (SSUs),
3. Analytical approaches for collecting FSS data,
4. Scanning and direct measurement of subsurface media, and
5. Sampling subsurface media.

Prior to presenting the recommendation in this guidance, it is important to recall the context meaning of the two terms: "surface" and "subsurface." For this guidance, subsurface investigation populations are those below ground surface that are deeper than the surface soil layer—or below the approximately top 15 cm of surface soil—that are exposed during the FSS but will be backfilled and will remain as part of the subsurface environment in the final site configuration. Materials brought to surface, such as overburden soils that are intended for reuse as backfill or other disposition pathways, also represent subsurface populations subject to this guidance. Un-remediated, volumetric subsurface soils are not the subject of this ISG. Separate guidance will be developed for un-remediated subsurface soils considering information provided in *Guidance on Surveys for Subsurface Radiological Contaminants White Paper* (SC&A 2020) among other sources as discussed in Chapter 1.

Subsurface radiological FSS investigations within the scope of this ISG include the following:

1. Subsurface materials (below ground surface) excavations:
    a. Excavation floor, soils
    b. Excavation sidewalls, soils
    c. Excavation floor, bedrock
    d. Inaccessible soil, beneath basement slabs
2. Surface and/or subsurface soil overburden removed for reuse
3. Subsurface structures
    a. Building slabs
    b. Walls of building structures
    c. Non-soil backfill materials (may consist of rubblized construction material from above-grade structures))
4. Off-site/Onsite acquired borrow materials
5. Miscellaneous materials such as embedded piping/penetrations

Existing guidance, such as NUREG-1757 Vol. 2, Rev. 2, and NUREG-1575, are adapted to surveys of the subsurface within the scope of this ISG to the extent practical (e.g., when those methods are thought to be able to satisfy data quality objectives (DQOs) for subsurface FSSs covered in this report). However, there will undoubtedly be unique scenarios, media, or conditions that are more difficult to address using existing guidance. Licensees should contact

NRC staff early in the process when non-routine situations arise where it is unclear whether existing methods can be used, or for use of alternative methods not covered in this guidance that appear to be the best option.

The investigation instrumentation and methods the NRC finds acceptable to use during radiological investigations of subsurface final status decision units are subdivided based on geologic (e.g., soil and bedrock) versus man-made decision units that are represented by subgrade structural walls, floor slabs, and demolition debris used as void space backfill. The subgrade structural decision units may also require further decision unit subdivision to address other media present such as embedded or underground pipes and process systems/ components. The FSS for remediated soil excavation surfaces (soil or bedrock) and intact subsurface building surfaces (walls and floor slabs, and sub-slab soils) are performed in situ. However, overburden soils or structural materials removed and planned for return to an excavation as reuse/backfill material may be fully characterized, such that FSS data quality and quantity requirements are met, in situ or ex situ. In situ characterization would occur prior to excavation in the case of overburden soils and for above-grade buildings prior to demolition and sizing of structural materials in cases where the debris is planned for reuse as backfill. Ex situ characterization could also be conducted, as described further in this interim staff guidance. Borrow material from other site locations may similarly be characterized in situ prior to use as backfill or ex situ after being excavated and stockpiled. Table 2.1 summarizes the various excavation scenarios and subsurface media surveys addressed in this guidance and indicates those that are explicitly addressed in NUREG-1757, Vol. 2., Rev. 2.

Table 2.1 Excavation Scenarios and Subsurface Media Surveys Addressed in this and Related Guidance

Subsurface	Survey Media	Citation to NUREG 1757, Vol. 2 Current *Survey* Guidance (App. G)	Citation to NUREG 1757, Vol. 2, Current *Dose Modeling* Guidance for Buried Materials (App. I or J)
Excavation floor/sidewall	In situ soil	• G.3.2.1: Surveys of Excavations	• J.1.1 Buried Radioactive Material or Subsurface Soil Contamination
Excavation bedrock	Bedrock	N/A	N/A
Soil beneath basement floor slab	In situ soil with overlying concrete slabs	N/A	N/A
Basement walls	Structural surfaces: concrete block, poured concrete, metal	N/A	• J.1.2 Backfilled Basements
Basement slabs/sumps	Structural surface	N/A	• J.1.2 Backfilled Basements
Embedded piping/penetrations	Limited access piping internal walls	• G.2.3 Sewer Systems, Waste Plumbing Systems and Floor Drains • G.2.5 Piping and Embedded Piping	N/A
Reuse soil (excavation overburden)	Ex situ soil	• G.3.2.3. Backfill from Impacted Onsite Areas	N/A
Borrow soil (on-site or off-site borrow, background/non-impacted)	Soil, may be in situ or ex situ at time of investigation for acceptability for use	• G.3.2.2. Backfill from Non-impacted Onsite and Off-site Areas and • G.3.2.3. Backfill from Impacted Onsite Areas	N/A

Note: General guidance is provided on survey of building surfaces and subsurface soil; however, columns three and four are marked as N/A if there are no explicit citations or sections listed in NUREG-1757, Volume 2, Rev. 2, applicable to the specific survey location or survey medium.

2.1 MARSSIM Applicability to Open Excavations, Building Substructures, and Materials Planned for Reuse (NUREG-1757, Volume 2, Rev. 2, Appendix G)

MARSSIM guidance (NRC 2000) is designed for the release of surface materials, whether building surfaces or surface soils. Thus, it may be argued that MARSSIM guidance should not be applied directly to surfaces that will, ultimately, be below the ground surface in the final site configuration. In a general sense, it is the physical survey methods and the fundamental compliance unit that currently makes MARSSIM designs most appropriate for surface investigations. However, the statistical approaches and much of the remaining philosophy of MARSSIM is readily adaptable to support the compliance demonstration for subsurface survey units (or larger decision units described below). Thus, there are valid reasons to incorporate, to the extent possible, much of the MARSSIM method when dealing with subsurface materials. These reasons include the following:

- The MARSSIM radiological survey and site investigation processes has U.S. EPA, DoD, DOE, and NRC federal agency consensus and is well accepted by industry as well as internationally,
- MARSSIM guidance is flexible,
- MARSSIM relies on DQOs to help ensure the right type, quality, and quantity of data are collected for decision-making,
- MARSSIM guidance integrates scanning to supplement sample/measurement data to account for doses from elevated areas,
- MARSSIM focuses on two non-parametric statistical test options (Sign and Wilcoxon Rank Sum [WRS]) for unambiguous, unbiased decision-making, with alternative methods listed, and
- MARSSIM uses a graded approach so that resource expenditures are proportional to the potential for exceeding release criteria.

Alternative methods are provided herein where the MARSSIM methods are either not appropriate (as would be the case if the compliance testing does not involve a dose-based limit), or when MARSSIM guidance is lacking (e.g., when direct measurement/access is limited due to unsafe conditions such as in a confined space).

The MARSSIM method is less applicable to materials planned for reuse/borrow that may or may not originate onsite and may or may not require statistical testing. Materials targeted for reuse/borrow do, however, require some level of confirmation to demonstrate adherence to regulatory requirements and/or to demonstrate that those materials have not been unacceptably impacted by site or non-site-related operations or events. Various methods are discussed in this guidance.

Another note on relevance is that MARSSIM applies to real property (e.g., lands and structures), as does this guidance. The supplement to MARSSIM, the *Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME)* (NRC 2009), applies to non-real properties—material and equipment (M&E). MARSAME offers some of the same advantages as MARSSIM (broad acceptance, flexibility, DQOs, etc.) for the disposition of M&E and similarly does not directly apply for use during the subsurface FSS. However, like MARSSIM, MARSAME contains relevant guidance that can be incorporated in the subsurface FSS design such as a scan-only surveys, in situ surveys, and interdiction surveys (screening materials before bringing them on site) that may be applicable to certain aspects of a subsurface FSS.

Most MARSSIM terminology also applies to open excavations, building substructures, and materials planned for reuse/borrow, although the following new terms are introduced below to distinguish between surface and subsurface FSS activities:

$DCGL_V$. A generic DCGL is a radionuclide-specific activity concentration within a *decision unit* corresponding to the release criterion (e.g., 25 mrem/yr). The DCGL as it applies to surfaces is based on the average concentration in a survey unit, and another action level is used to assess the added risk from elevated areas (i.e., the elevated measurement comparison or $DCGL_{EMC}$). MARSSIM DCGLs apply to surface exposure, either as the ground surface or on the surface of a habitable structure. Therefore, the DCGLs discussed in this guidance are for subsurface volumes and are often distinguished using the subscript V: $DCGL_V$**;** this does not preclude that both an average concentration $DCGL_W$ and elevated area $DCGL_{EMC}$ may still be appropriate. There also may be different types of $DCGL_V$ values (e.g., one for reuse materials, one for subsurface soil, one for structural materials, and one limited to groundwater pathways), and there will be different $DCGL_V$ values for each radionuclide of concern (ROC). For ease of reference, this chapter uses a naming convention to distinguish between different DCGL types, although the licensee may use a different approach or even calculate an effective DCGL to account for multiple potential exposure scenarios or media. For example:

- $DCGL_{V\_Si}$ can represent the subsurface soil DCGL for ROC i,
- $DCGL_{V\_Bi}$ can represent the building substructure DCGL for ROC i,
- $DCGL_{V\_Ri}$ can represent the reuse material DCGL for ROC i, and
- $DCGL_{V\_GWi}$ can represent the migration to groundwater DCGL for ROC i.

A licensee may also establish a cleanup level at a fraction of the applicable dose standard (e.g., unrestricted release standard) to account for multiple contaminated media or exposure pathways. This approach is sometimes necessary when the conceptual site model includes multiple, non-contiguous contaminated media. For example, materials from a backfilled basement structure can be excavated and distributed across the ground surface, thus creating two independent source terms: one on the surface and one that remains in the backfilled basement. Materials that remain in situ could still migrate to the water table and expose receptors, meaning the licensee should now account for doses from two independent, non-contiguous sources. Multiple sources associated with the same or different survey unit may also contribute cumulatively to the dose to a single receptor. In some cases, licensees derive effective or operational DCGLs to ensure the dose criterion is satisfied. Effective DCGLs may account for multiple potential exposure pathways of the same source (e.g., in situ leaching to groundwater and excavation scenario dose from the same buried residual radioactivity), to ensure that the dose criterion is met. Operational DCGLs are used to establish a cleanup level at a fraction of the applicable dose standard (e.g., unrestricted release standard) to account for multiple contaminated media or exposure pathways.

MAC. A licensee is required to demonstrate compliance with a disposal facility's waste acceptance criteria (WAC) when planning for the off-site disposition of materials. Like an off-site WAC, a licensee could establish materials acceptable criteria (MAC) to show that reuse/borrow materials to backfill excavations or basement structures meet the onsite release criteria (versus meeting the off-site waste acceptance criteria). Whether adapting MARSSIM, MARSAME, or other methods, compliance with LTP criteria for reuse of materials or borrow, such as a $DCGL_{V\_R}$, should be based on dose modeling or other administrative considerations as described herein or as otherwise described in NUREG-1757, Volume 2, Rev. 2, Appendices G and J, or based on other alternative approaches developed by the licensee that are approved by the NRC.

SSU and Decision Unit. The term survey unit (SU) is defined in MARSSIM as a geographical area consisting of structures or land areas of specified size and shape at a decommissioning site for which a separate decision will be made. While the SU is used for ground-level or habitable structure surfaces, the term subsurface survey unit (SSU) is used here to describe a geographical volume or subsurface area of contamination material in an open excavation, building substructure, or population of materials planned for reuse. Whether an SU or SSU, FSS data will be collected for comparison to release criteria, meaning a separate decision will be made for each SU and each SSU. The term decision unit is used to describe combinations of SUs, SSUs, or other geographical division upon which final status decisions will be made, generally based upon total dose concerns. As an example, a decision unit might include basement structural walls and floor, piping, and the material used to backfill void space.

2.2 Categorizing and Classifying Survey Units

Prior to classification, the property is initially categorized as either impacted on non-impacted using established norms. The property may also be assigned the MARSSIM classification for impacted areas (i.e., Class 1, 2, or 3) during the HSA. This may be followed by subsequent adjustments in the classification through each stage of the radiation survey and site investigation (RSSI) process. Consistent with MARSSIM, an impacted property is that with a possibility of containing residual radioactivity above natural background or fallout levels, while a non-impacted property is that with no reasonable possibility (extremely low probability) of residual contamination. For this guidance, all open excavations and process-related substructures are presumed to be impacted, although materials targeted as backfill can originate from either impacted (onsite reuse materials) or non-impacted areas (off-site borrow or non-impacted structures slated for demolition). Once categorization is completed, property designated as impacted can then be divided into discrete decision units.

The MARSSIM method describes a means to divide a study area into discrete geographical decision units. As with categorization, the classification process for open excavations, substructures, and materials planned for reuse should be consistent with well-established norms. These norms include separating impacted property into one of three designated classes: Class 1 area, Class 2 area, or Class 3 area, where:

> Class 1 applies to areas with the highest potential for contamination. Class 1 designations apply to areas that have, or had prior to remediation, a potential for radioactive contamination or known contamination. Areas containing contamination in excess of the $DCGL_W$ prior to remediation should be classified as Class 1.
>
> Class 2 areas have, or had prior to remediation, a potential for radioactive contamination or known contamination, but are not expected to exceed the $DCGL_W$. There should be a high degree of confidence (e.g., supported by the HSA or radiological survey) that no individual measurement would exceed the $DCGL_W$ to justify classification of an impacted area as a Class 2 versus a Class 1 area.
>
> Class 3 areas are impacted areas that are not expected to contain any residual radioactivity or are expected to contain levels of residual radioactivity that are a

small fraction of the $DCGL_W$ based on site operating history and previous radiological surveys. Class 3 areas include areas where there is insufficient information to justify designation of the area as non-impacted.

MARSSIM provides example rationale for assigning Class 1, 2, or 3 designations in Section 4.4 of Rev. 1. Class 1 and 2 areas have, or had prior to remediation, a potential for radioactive contamination (based on site operating history) or known contamination (based on previous radiological surveys). Areas containing contamination above $DCGL_W$ values prior to remediation should be classified as Class 1 areas, while Class 2 areas are not expected to exceed the $DCGL_W$. Class 3 areas are impacted areas that are not expected to contain residual radioactivity or only contain residual radioactivity at levels that are a "small fraction of the $DCGL_{W.}$" Given the semi-quantitative descriptions of the class designation, professional judgment is part of the classification process. Professional judgment includes consideration of process knowledge, analytical/scan data collected through the RSSI process, DCGLs, and environmental transport modeling predictions, among other inputs. There are no specific thresholds for classification other than when residual ROC concentrations (i.e., in isolated elevated areas) are detected above DCGLs—Class 1 designation is appropriate in that case. Class is otherwise assigned based on an array of factors including the potential for failing the statistical test or other criteria.

While MARSSIM suggests that Class 1 is appropriate for SUs when some concentrations are above the $DCGL_W$ prior to remediation, a Class 1 designation for the SSU soil beneath a remediated excavation footprint may not be necessary if the licensee can justify the lower class when, for example, ROCs are easily identified by scanning during the RASS, the licensee used ALARA (as low as reasonably achievable) principles when planning the excavation and perhaps excavated beyond the known contamination thickness, the licensee has a history of successful remedial operations, and relaxing the classification under stringent criteria is acceptable to stakeholders. Relaxing the classification for the now exposed subsurface soil within the excavation may be considered at some sites, even if rarely so, under certain conditions. Consider the following example:

> A licensee remediated a Class 1 land area that contained residual contamination above DCGL criteria (i.e., $DCGL_W$ and/or $DCGL_{EMC}$). However, the same characterization data used to plan the remedial action also suggests that contamination was limited to the top 0.5 m of soil with high confidence (e.g., geoprobe samples collected during characterization show the radioactivity is confined to the top 0.5 m of soil with no radioactivity detected in subsurface soil or groundwater samples collected at the water table approximately 5 m below ground elevation; additionally, the constituent is expected to be highly immobile based on site-specific K_ds [see Section 3.3]). To ensure residual concentrations are ALARA, the licensee excavated soils 1 m, and the RASS data demonstrates there are no residual concentrations above the $DCGL_V$. The licensee, therefore, designated the FSS SSU associated with the excavation floor/walls as Class 2.

The CSM may also include a scenario where buried ROCs leach to the water table and expose hypothetical receptors via a groundwater well. That is, the materials are not excavated but, rather, remain in situ if a groundwater-related DCGL (in situ leaching-based) or some other threshold is not reached. In this manner a class may be assigned for the entire, or large sections of, the excavation/substructure based on either a DCGL or an operational DCGL. It may also be that classification for one exposure scenario (e.g., excavation and redistribution) suggests one classification, and a second exposure scenario (e.g., migration to groundwater) suggests a different classification. If this is the case, the more conservative classification will be applied to ensure sufficient FSS data are collected to address both situations. In some cases, licensees use an “effective DCGL” to account for all scenarios which could also be used to determine classification.

Similar exposure scenarios (e.g., excavation and migration to groundwater) and thus, a similar classification approach, can be applied to reuse materials. That is, if reuse material contains residual ROC contamination, it is reasonably foreseeable or plausible that contamination can 1) be excavated and repurposed at the surface or 2) migrate to groundwater and lead to exposures via water-dependent pathways. Therefore, rules used to classify excavation/substructural materials may also be used to classify materials planned for reuse. Consider the following example:

> A reactor building basement is to be backfilled with a combination of rubblized concrete from an auxiliary building, grout, and soil from an onsite (therefore impacted) Class 3 area. Characterization data from the auxiliary building prior to demolition and the Class 3 soil area suggest a low probability of exceeding $DCGL_{V\_R}$ values, so reuse materials are conservatively designated as Class 2. Modelers have also developed $DCGL_{V\_B}$ values for the concrete basement shell. The most conservative $DCGL_{V\_B}$ values are based on restricting exposure to groundwater, and characterization data demonstrate that the top 3 m (10 ft) below ground surface has a low potential for exceeding $DCGL_{V\_B}$ values, but a Class 2 or 3 designation cannot be justified for deeper materials. Therefore, the top 3 m (10 ft) of the building basement is designated as Class 2, and the rest of the substructure is designated as Class 1.

As demonstrated in the example, a substructure can be divided into multiple SSUs based on ROC distribution, contamination potential, etc. Similar decisions can be made for soil excavations. Dose modelers may have developed different $DCGL_V$ values for different soil depths, so a relatively deep excavation can be subject to multiple criteria. The licensee can select SSU boundaries based on the applicable $DCGL_V$, can select the most restrictive values, and apply them to the entire excavation, or can develop an alternative approach. Excavation walls and floors can be classified differently, assuming each represents a different potential for exceeding release criteria (e.g., based on data, modeling, process knowledge, etc.). These are risk management decisions for the licensee to evaluate during DQO development.

The classification process can be complex when considering different combinations of $DCGL_W$ and $DCGL_V$ values; hypothetical scenarios that combine excavating and repurposing building materials, groundwater modeling, and other exposure pathway analyses; characterization data; etc. While the process may be complex, the overall strategy is as follows: establish guidelines for classifying materials during DQO development to ensure that impacted materials that have the highest potential for exceeding DCGLs are Class 1, impacted materials that have a low potential for exceeding DCGLs are Class 2, and impacted materials that have little or no potential for exceeding DCGLs are Class 3.

2.3 Size of Subsurface Survey Units

As previously stated, a SSU represents a geographical decision unit whether for an open excavation, a building substructure, or a population of materials planned for reuse. The size and shape of the decision unit are based on factors such as the potential for contamination, the expected distribution of contamination, and physical boundaries (e.g., building sections and excavation borders). SSU sizes for any given site can be expected to vary from relatively small (e.g., a small substructure or excavation) up to a scale comparable to that used to derive $DCGL_W$ or $DCGL_V$ values. The maximum decision unit size should, to the extent practicable, be consistent with the DCGL modeling assumptions including key parameters such as thickness, depth, and area/volume of residual radioactivity. Consider, for reference, MARSSIM guidance on maximum SU area for surface soil and how area relates to soil DCGL modeling assumptions:

Class 1 recommended maximum area of up to 2,000 m^2
Class 2 recommended maximum area of up to 10,000 m^2
Class 3 area unlimited

An area on the order of the recommended Class 2 maximum of 10,000 m^2 (~2.5 acres) is sufficient to maintain a residence, livestock, and crops (for grazing/fodder and human consumption) (ANL 2001). MARSSIM recommends a maximum Class 1 size of 2,000 m^2 (~0.5 acres), or 20 percent of the Class 2 area recommendation, an area that codes like RESRAD-ONSITE consider large enough to support both habitation and the plant ingestion pathway (ANL 2001). The smaller Class 1 area also helps ensure a higher FSS sample density where the potential for contamination is the highest (i.e., applying the graded approach to radiological survey).

It is important to note that MARSSIM's recommended maximum SU areas for structures does not apply to SSUs (e.g., Class 1 recommended maximum area of 100 m^2), because the traditional conceptual model for indoor areas presumes some level of occupancy (e.g., an office or laboratory). Substructures subject to this guidance will not represent habitable space. Rather, subsurface spaces subject to this guidance will be backfilled with either unimpacted or reuse material, so the conceptual model used to develop building occupancy $DCGL_W$ values are incompatible. As described in NUREG-1757, Volume 2, Rev. 2 (NRC 2022) exposures to ROCs in the SSU occur when subsurface materials are:

- Re-exposed (soil residuals) at the surface, thus conservatively ignoring the presence of "clean" backfill or cover materials,
    - Residual concentrations are compared to $DCGL_W$ or $DCGL_{EMC}$ values, and/or
- Excavated and redistributed across the surface,
    - Residual concentrations are compared to $DCGL_W$, $DCGL_{EMC}$, or $DCGL_V$ values, and/or
- Remain in situ where ROCs migrate to groundwater leading to exposure via water-dependent pathways,
    - Residual concentrations are evaluated against $DCGL_{GW}$ values.

These scenarios can occur in combination under worst-case conditions, such as the excavation and redistribution of some materials, leaving a large volume of materials in situ, where ROCs could transport via groundwater flow to a well location. However, these scenarios do not include the highly unlikely scenario that involves excavating and re-inhabiting a basement or other substructure that has been previously backfilled. Because the CSM for backfilled soils and backfilled substructures is functionally identical, the guideline for SSU substructures and SSU land areas (e.g., excavations) are identical, as listed in Table 2.2.

Table 2.2. Maximum SU/SSU Size Guidelines by Class and Medium

Medium	MARSSIM Guidelines	ISG Guidelines
	Surface Survey Unit Size Guideline	**Subsurface Survey Unit Size Guideline**
Class 1		
Structure[1]	Up to 100 m^2	Up to 2,000 m^2
Land Area	Up to 2,000 m^2	Up to 2,000 m^2
Class 2		
Structure[1]	100 to 1,000 m^2	2,000 to 10,000 m^2
Land Area	2,000 to 10,000 m^2	2,000 to 10,000 m^2
Class 3		
Structure[1]	No Limit	No Limit
Land Area	No limit	No Limit

[1]Assumed to be habitable for the surface survey unit and assumed to be uninhabitable (backfilled) for the subsurface survey unit.

When relatively large SSUs are considered, licensees should recall general MARSSIM guidance for selecting distinct decisions unit boundaries:

- SSU materials should, to the extent practical, have similar operational history or a similar potential for residual radioactivity.
- SSU materials should have the same classification.
- SSU size limit decisions should consider exposure pathway modeling assumptions and site-specific conditions.
- SSUs should have relatively compact geometries and not have highly irregular (gerrymandered) shapes unless the unusual shape is appropriate for the site operational history or other relevant conditions.

Consider Figure 2.1 for the following discussion. If the substructure containing these walls were to be released for future occupants, MARSSIM guidance would be used to assign SU sizes based on the assumption that individuals will spend extended periods of time in room-sized spaces (e.g., divide the Class 1 areas into 100 m^2 SUs). This substructure will be backfilled, however, so MARSSIM-based size limits for a habitable building no longer apply. Instead, the CSM for subsurface materials includes the potential for 1) ROCs to migrate to groundwater (compare to a $DCGL_{GW}$) or 2) material to be excavated and redistributed on the surface (compare to $DCGL_W$/$DCGL_{EMC}$ values).

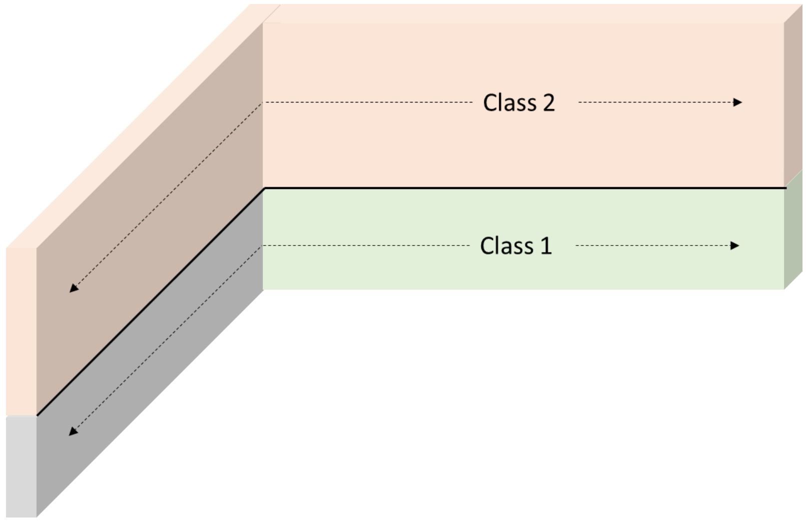


Figure 2.1 Substructure Walls with Different Classes

Assume for this discussion that characterization data and process knowledge support the conclusion that the upper level of the Figure 2.1 structure has the same process history, ROCs, and low potential for contamination; thus, the approximately 8,400-m^2 upper level is assigned a Class 2 designation. For the approximately 4,200 m^2 lower level, each wall section is associated with different process histories and ROC distribution, and the potential for contamination is relatively high; thus, the lower level is assigned a Class 1 designation. Although the entire lower level has the same classification, available information suggests each lower wall section should be evaluated as an independent SSU. Figure 2.2 illustrates how classified substruction levels may be subdivided into SSU based on this information, where SSU-2-1 is a single Class 2 SSU, and SSU-1-1 and SSU-1-2 are two Class 1 SSUs.

Note the recommended maximum Class 1 size in Table 2.2 was not considered to be a hard line—a licensee should provide a rationale why some SSUs can be larger, as appropriate, such as the argument that the wall redistribution scenario is conservative and the proposed SSU area is only a small percentage more than the recommended maximum.

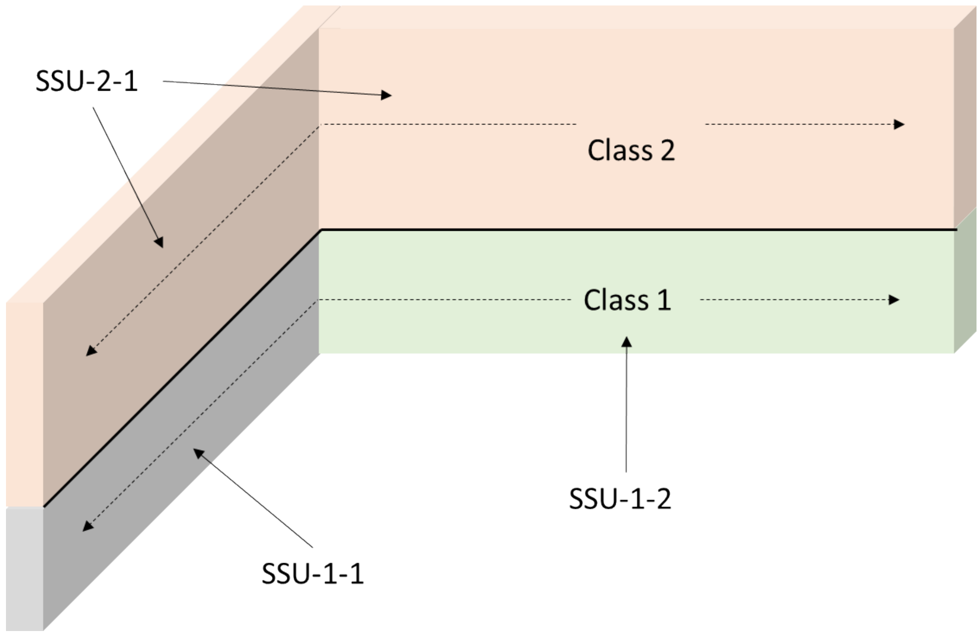


Figure 2.2 Substructure Walls Divided into SSUs

Because exposure to ROCs may occur from either in situ leaching or material excavation and redistribution, the FSS design will ensure sufficient data are collected for comparison to $DCGL_V$/$DCGL_W$/$DCGL_{EMC}$ values and the applicable groundwater dependent statistic (such as a $DCGL_{GW}$ or operational DCGL) and/or an effective DCGL considering all exposure pathways. Regarding the size of the substructure, it is likely that the size associated with SSUs for a MARSSIM-based design is sufficient for assessing the $DCGL_{GW}$. For example, if a structure is divided into five SSUs, and each SSU is independently characterized with *N* samples, then there will be at least 5×*N* statistical samples for estimating the structure's total dose from multiple SSUs, if the survey units could cumulatively contribute to dose. The licensee simply needs to ensure that, during DQO development, there will be sufficient samples to address both statistical testing (or whatever SSU criteria are established) and the groundwater dependent statistic. If existing groundwater contamination is a concern, Chapter 4 contains additional detail on how to assess the added dose from existing groundwater contamination.

2.4 Analytical Approach

There are multiple general considerations/factors when selecting an analytrical approach for the FSS of a subsurface decision unit. The complexity of the approach is a function of the site's compliance demonstration commitment(s) in the NRC-approved LTP or related license conditions, as applicable. This guidance outlines these factors and provides acceptable data collection planning and analysis methods to be used for the majority of SSU decision units.

2.4.1. Analytical Approach—General Factors

General factors considered in this guidance are as follows:
The analytical approach should:

1. ensure there is an adequate sample size and data density,
2. relate to the CSM used for dose and exposure pathway modeling,
3. account for elevated areas, if and when applied to SSUs,

4. account for mutlple ROCs including HTDs, and
5. account for multiple acceptance criteria (e.g., both for decision and estimation problems).

Factor 1: Sample Size and Density. The selected analytical approach should result in a sufficient sample size and sampling density to answer the principal study question(s) at specified confidence levels. The form of the study question and subsequent DQO steps will help define the needed analytical approach and required confidence, and hence form the basis of the inputs to calculate sample size and density. A typical MARSSIM FSS uses non-parametric testing methods (WRS or Sign) to calculate sample size while considering the relative shift, false positive, and false negative decision errors; the analyst then establishes the sample density within each SU by limiting the size of individual decision units. Sample size and density in SSUs may also be established using a similar MARSSIM-like approach, but there are other factors to consider.

Factor 2: Relate to the CSM and Dose Model. The sample collection methods (i.e., depth, volume, media, etc.) and analytical results (i.e., target ROCs, reporting units, etc.) should represent the DCGL modeling and the CSM. Simplified assumptions that have traditionally been applied to surface decision units (SUs) may not necessarily apply to SSUs. For example, it may be that subsurface media cannot be represented by a single uniform DCGL, such as when an LTP calls for the collection of 0 to 15 cm (0 to 6 inch) sample depths within each survey unit. This approach has historically been followed regardless of whether the sampled “surface” represents ground surface or the surface of an excavation. However, SSU sample depths should be tied to a CSM, if applicable, that includes excavation of materials and redistribution at the surface. The licensee should, determine what volume of material (contamination source area times depth) could be excavated and, therefore, what sample depth will match the CSM. This should be balanced against the possibility of diluting thin contamination layers across a deep core or underestimating contamination levels by using a shallow core depth that fails to reach the depth of contamination. This can be complicated when some material within an SSU is physically different or require different or multiple reporting units such as total activity (Ci or Bq), volumetric concentration (pCi/g or Bq/g), surface concentration (pCi/m^2 or Bq/ m^2), etc. The dose model assumes exposures to different media, all of which should be considered by the analytical approach.

Factor 3: Multiple ROCs and HTDs. The idea or reality that a site can have multiple ROCs and HTDs should be familiar to most licensees, and methods for addressing these challenges are adequately described in MARSSIM. For example, MARSSIM suggests using the unity rule when multiple ROCs are present and individual ROC concentrations are compared to respective DCGLs. MARSSIM also describes how the DCGLs are modified for some relatively easy to detect radionuclides such that the detectable ROCs are used as proxies to quantify HTDs and/or ROCs that are relatively expensive to quantify directly.

Factor 4: Elevated Areas. The identification and quantification of elevated areas may be, or may not be, part of the SSU investigation study objective. Recall that MARSSIM includes a process for Class 1 SUs whereby sample spacing is reduced (resulting in a higher sample density) when scanning alone cannot identify dose-consequential elevated areas. This process may or may not be necessary for SSUs, and a licensee may be required to pursue avenues (beyond scanning) when developing an analytical approach that ensures inclusion of elevated areas. The reason for considering other avenues is because the exposure assumptions for a surface SU are different than those for an SSU (see NUREG-1757, Volume 2, Rev. 2, Appendix J that discusses exposure scenarios that could bring residual radioactivity to the surface whereas surface soil $DCGL_{EMC}$ values are based on the ability of a receptor to be exposed to contamination already at the surface). For an SSU scenario where subsurface material is excavated, brought to the surface, and then redistributed over the ground surface, the concentration from a relatively small, contaminated volume will likely be diluted by the mixing that occurs with clean overburden, as material is brought to the surface. Additional mixing may occur as excavated material is spread across the surface. Therefore, this guidance focuses on the inferential identification of elevated areas in SSUs rather than the direct approach of comparing the scan MDC to a table of $DCGL_{EMC}$ values. This inferential approach evaluates the potential presence and magnitude of elevated areas and identifying potential population outliers that should be further investigated for their contribution to the total dose. If identification of elevated measurements is critical and scanning is insufficient (e.g., due to lack of access or inadequate sensitivity), a presence/absence or other probability-based design may be needed to supplement scanning and support the decision-making process. When used, it is likely that the sample density from the probability-based design will also satisfy the sample number requirement for estimating the mean and variability (e.g., to compare to the DCGL) or statistical tests (e.g., WRS or Sign).

Factor 5: Multiple Acceptance Criteria. Ultimately, the subsurface FSS data assessment method will be used to decide whether the NRC license termination rule has been satisfied. The analytical approach will, in most cases, be a function of whether the licensee should address a decision problem (involving hypothesis testing) or an estimation problem (e.g., estimating the maximum, mean, and variability), or both a decision problem and an estimation problem. The two paths are shown between DQO steps 5 and 6 in Figure 2.3. An example decision problem is using the Sign test to demonstrate that a Class 1 SSU satisfies release criteria. Examples of estimation problems include estimating ROC levels in bulk materials targeted for reuse (as backfill) or estimating a weighted average across a basement structure that includes multiple SSUs. Each of these three FSS scenarios (involving a statistical test, assessing reuse material, and estimating a weighted average) have different DQOs, although it is possible that all three should be considered together by the overall analytical approach.

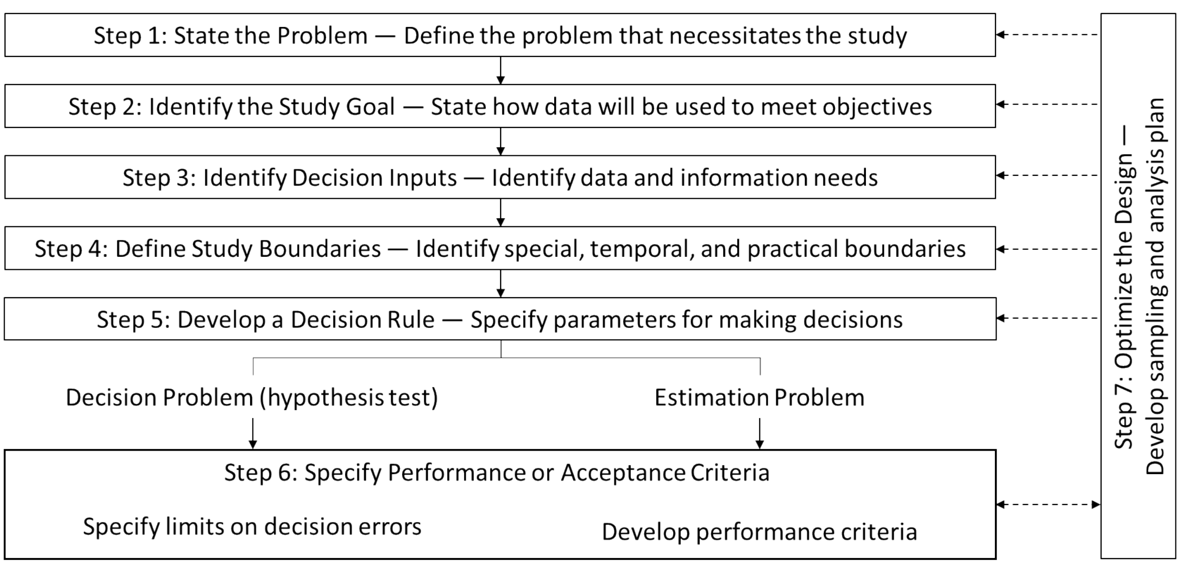


Figure 2.3 Seven-step DQO Process Including Decision and Estimation Problem Pathways

2.4.2. Analytical Approach—Hypothesis Testing

Hypothesis testing is used to assess the outcome of a binary decision—either the SSU is or is not acceptable for release. The null hypothesis, commonly denoted as H_0, is the assumed base condition and is accepted in absence of sufficient evidence to the contrary. If the test concludes that the base condition is met, the decision is to fail to reject the null hypothesis (note, the test does not prove the null hypothesis, although the licensee will accept the null hypothesis without strong evidence to the contrary). If the test concludes that the base condition is not met, the decision is to reject the null hypothesis in favor of the alternative hypothesis, denoted as H_A. MARSSIM describes two “scenarios” the licensee will consider when selecting the statistical test. While the MARSSIM scope is limited to surfaces, these scenarios can still be applied to the subsurface. The null and alternative hypotheses for Scenarios A and B are as follows:

- Under Scenario A, H_0 is survey unit concentrations exceed the release criterion, while H_A is survey unit concentrations are less than or equal to the release criterion; and
- Under Scenario B, H_0 is survey unit concentrations are less than or equal to the release criterion, while H_A is survey unit concentrations exceed the release criterion.

A specific application of Scenario B is the “indistinguishable from background” case, which is typically considered when the $DCGL_W$ is small compared to background variability and detection capability. In other words, Scenario B is acceptable when the outcome of the statistical test under Scenario A is influenced by the selection of the reference area.

Both MARSSIM and NUREG-1505 (NRC 1998) present details describing the analytical approach when selecting either Scenario A or Scenario B. Therefore, only a summary-level discussion is presented here with the expectation that Scenario A will suffice in most cases. Scenario B may also be familiar to many licensees, but an additional indistinguishable from background alternative (Scenario B’, or B-prime) is presented in this guidance given conditions required to implement the indistinguishable from background case of Scenario B may not exist in an SSU or reuse/borrow decision unit application. Hypotheses tests described in this guidance, associated null and alternative hypotheses, and the conditions under which the tests may be selected are described in Table 2.3. A brief description of each scenario and test combination is presented.

Scenario A. Assuming the $DCGL_W$ is distinguishable from background (or the ROC is not present in background), the licensee will likely select between two non-parametric statistical tests: the WRS test or the Sign test. Traditionally, the WRS test is selected when the contaminant is present in background (e.g., Ra-226) and the Sign test is selected when the contaminant is not present in background (e.g., Co-60). When the WRS test is selected, the licensee collects samples in both the SSU and in a reference area—both sets are required to perform the test. Only samples from the SSU are required for the Sign test given there is no reference area if the contaminant is not present in background. When the contaminant is present in background, but the $DCGL_W$ is much higher than typical expected concentrations, the licensee may choose to “swallow” background and select the Sign test. By ignoring background, the licensee accepts an increased risk for making a decision error (concluding the SSU exceeds the release criterion when it does not because background contributions are ignored), although the licensee streamlines the FSS process by eliminating the need to collect statistical samples in the reference area.

The null and alternative hypotheses for Scenario A for the WRS test can be expressed in different ways, including the following:

H_0 (WRS): $\mu_{SSU} > \mu_R + DCGL_W$

The mean (or median) concentration of residual radioactivity above background in the survey unit exceeds the $DCGL_W$, and

H_A (WRS): $\mu_{SSU} \leq \mu_R + DCGL_W$

The mean (or median) concentration of residual radioactivity above background in the survey unit does not exceed the $DCGL_W$,

where μ_{SSU} is the true SSU concentration. Because the WRS and Sign tests are non-parametric tests of the median, the mean concentrations of residual radioactivity in the survey unit above background should also be shown to be less than the $DCGL_W$.

For the Sign test, $\mu_R = 0$ because there is no reference area, the null and alternative hypotheses can be expressed as follows:

H_0 (Sign): $\mu_{SSU} > DCGL_W$

The mean (or median) concentration of residual radioactivity in the SSU exceeds the $DCGL_W$, and

H_A (Sign): $\mu_{SSU} \leq DCGL_W$

The mean (or median) concentration of residual radioactivity in the SSU does not exceed the $DCGL_W$.

The $DCGL_W$ represents the upper bound of the gray region (UBGR) and the expected SSU concentration (μ_{SSU}) should be selected as the lower bound of the gray region, so the gray region is expressed as: $\Delta = DCGL_W - LBGR$.

Under Scenario A, the Type I error rate (α) is the probability that a survey unit with residual radioactivity above the $DCGL_W$ will be released, and the Type II error rate (β) is the probability that a survey unit will not be released although residual radioactivity is less than or equal to the $DCGL_W$. Scenario A Type I (α) decision errors are often selected to be 0.05, and Type II (β) decision errors are often selected to be 0.05 or 0.1, although the licensee is required to justify the decision errors it selects via the DQO process.

Table 2.3. Select Hypothesis Test Options for Decision Units

Scenario	Test	H_0 and H_A	Application
A	WRS[a]	H_0: $\mu_{SSU} > \mu_R + DCGL_W$ H_A: $\mu_{SSU} \leq \mu_R + DCGL_W$	The expected SSU concentration is presumed above the $DCGL_W$, and the contaminant is present in background
A	Sign	H_0: $\mu_{SSU} > DCGL_W$ H_A: $\mu_{SSU} \leq DCGL_W$	The expected SSU concentration is presumed above the $DCGL_W$ and either 1) the contaminant is not present in background, or 2) the $DCGL_W$ is much greater than the expected background concentration and the background is not subtracted (background is “swallowed”).
B	WRS	H_0: $\mu_{SSU} \leq LBGR$ H_A: $\mu_{SSU} > DCGL_W$	The SSU meets the release criteria or in the special case of Scenario B described in Chapter 13 of NUREG-1505 (NRC 1998), the expected SSU concentration is indistinguishable from background up to a concentration specified by the LBGR.
B’	Student t or WMW[b]	H_0: $\mu_{DU} \leq \mu_R$ H_S: $\mu_{DU} > \mu_R$	The decision unit concentration is presumed to be less than or equal to the reference area concentration, both populations are normally distributed, and populations variances are within statistical tolerances. Alternate forms of the t-test, such as Satterthwaite’s t-test, can be performed when the two populations are normal but have unequal variances or have differing sample sizes. Under WMW test conditions, populations are not normally distributed, but have the same shape only shifted by a specific quantity (a non-parametric test is needed).

[a] WRS stands for Wilcoxon Rank Sum.
[b] WMW stands for Wilcoxon-Mann-Whitney. The WMW test is the same as the WRS test, in terms of performance; the only difference is how the test statistic is calculated.

Scenario B. Scenario B “flips” the Scenario A null hypotheses and focuses on the LBGR instead of the UBGR or $DCGL_W$ as the action level. Scenario B is appropriate where background variability is significant relative to the $DCGL_W$ (the “indistinguishable from background” case) or where zero residual radioactivity (or zero residual radioactivity above background) is allowed, making it difficult to establish a discrimination level or LBGR below an action level set at the UBGR. In this case, the approach is to establish a discrimination level (DL) at some concentration above the LBGR. The WRS test is used to determine if the median concentration in the SSU is above the LBGR. The Scenario B null and alternative hypotheses can be expressed as follows:

H_0: $\mu_{SSU} \leq LBGR$

The mean (or median) concentration in the SSU is indistinguishable from background up to the LBGR, and

H_A: μ_{SSU} > LBGR

The mean (or median) concentration in the SSU is distinguishable from background in excess of the $DCGL_W$ or some other discrimination level established during the DQO process.

Certain conditions should be met to for this approach to be justified, as described in NUREG-1505 (NRC 1998). The conditions are as follows:

1. The $DCGL_W$ is small compared to the background variability and is small compared to detection capability
    a. The Kruskal-Wallis test is used to determine if significant variability exists in the background reference areas (four reference areas are recommended), although background variability can be given the benefit of the doubt.
2. Having demonstrated adequate background variability, the licensee should select the concentration that is indistinguishable from background
    a. Under Scenario B the concentration that is indistinguishable from background is the LBGR, and is expressed as follows:

$$LBGR = M\sqrt{\hat{\omega}^2} = \mathrm{M}\sqrt{\frac{(S_b^2 - S_w^2)}{n_0}}$$

where,

M is a multiplier selected using the DQO process
ω^2 is the component of the variance
${S_b}^2$ is the mean square between reference areas
${S_w}^2$ is the mean square within a reference area
n_0 is a value usually less than the average number of samples taken in each reference area.

Because the null hypothesis is flipped relative to Scenario A, α is the probability of concluding that SSU concentrations are greater than the LBGR when they are actually indistinguishable from background, and β is the probability that SSU concentrations are less than or equal to LBGR when they are actually above the UBGR. Scenario B Type I (α) decision errors are often selected to be 0.05 with the error divided between the WRS and the quantile test at a value of 0.025 each (i.e., the selected α for the WRS is half of the desired Type I error because the quantile test is also performed with the WRS test), and Type II (β) decision errors are often selected to be 0.05 or 0.1, although again the licensee is required to justify decision errors it selects via the DQO process. It is important to note that it is in the interest of the regulator to ensure that the Type II error is relatively low in Scenario B, because it ensures there is sufficient power to reject the null hypothesis that the site is clean when, in fact, it requires remediation.
In an SSU (versus SU) or when considering materials targeted for backfilling an SSU, Scenario B may not be feasible or practicable. For example, a licensee may not have access to multiple populations (e.g., four) of reference materials, or the Kruskal-Wallis test may demonstrate there is insufficient background variability. In these cases, background variability can be given the benefit of the doubt as discussed in Chapter 13 of NUREG-1505 (NRC 1998). The test is labeled Scenario B’.

Scenario B'. Scenario B' is used to determine whether the mean concentration from the decision unit is statistically greater than the reference area. Generally, stakeholders are only concerned if the decision unit is greater than the reference area, and therefore, a one-sided test is appropriate. These two populations can be SSU materials and reference materials, onsite soils targeted for reuse and a reference area, or an onsite reference area and offsite borrow materials. To differentiate from Scenarios A and B, a different term μ_{DU} (for decision unit) replaces μ_{SSU} in the null and alterative hypotheses, as follows:

H_0: $\mu_{DU} \leq \mu_R$

> The mean concentration in the decision unit is not significantly different than the mean concentration in the reference area, and

H_A: $\mu_{DU} > \mu_R$

> The mean concentration in the decision unit is significantly different than the mean concentration in the reference area.

The specific type of the Scenario B' test can take different forms, such as those described in MARSSIM Table 2.3. Two methods are presented here: the parametric Student t-test and the non-parametric Wilcoxon-Mann-Whitney (WMW) test. The former is only appropriate under certain conditions (as will be described) and generally results in higher power. The two underlying conditions for the t-test are as follows:

1. Both populations (e.g., representing the reuse/borrow area and the reference area) should be normally distributed.
2. Population variances should be the same, within statistical tolerances.
3. If the above is not true a t-test with unequal variances can be used.

If all conditions are met based on a retrospective analysis of the data collected, then the t-test can be used. Otherwise, the non-parametric WMW test is selected. Selecting the test after collection and analysis of the samples is consistent with the data quality assessment (DQA) process as described in MARSSIM Chapter 8 (Step 3 is to "select the statistical test"), although MARSSIM users have traditionally select WRS and Sign during planning and consider changing tests during the DQA. The WMW is robust and does not require the assumption of normality, however, the test is not assumption free. Both populations should have the same underlying distribution only offset, or shifted, by some value. The test is robust, meaning that the test will yield adequate power if there are small deviations from the underlying assumption (i.e., test results will still be valid when both population variances are not exactly equal). A simple graphical review will generally satisfy a test of this assumption.

The Type I error rate (α) for Scenario B' is the probability that the test will incorrectly concluded that μ_{DU} is less than or equal μ_R (incorrectly conclude the decision unit is suitable for reuse/backfill when it is not) and the Type II error rate (β) is the probability that the test will incorrectly conclude that μ_{DU} is more μ_R (incorrectly conclude the decision unit is not suitable for reuse/backfill when it is). Guidance suggests the Scenario B' a Type I (α) decision error of 0.1, and Type II (β) decision no more than 0.2 (EPA 2002b), although the licensee will be required to justify its selection via the DQO process.

2.4.3. Analytical Approach—Estimations

Compliance assessments may be based on estimation of population parameters and not hypothesis tests such as the WRS or Sign test. For example, it may be necessary to estimate the amount of residual radioactivity when the total inventory or cumulative dose from multiple SSUs may be a concern. An arithmetic mean may not be sufficiently conservative (given half the values in a normal distribution fall below the mean), so the parameter of interest is often set to the upper confidence limit (UCL) of the mean concentrations in the decision unit. Application of the UCL of the mean at the 95 percent confidence interval (UCL95) is the most common, although UCL99 is also an option for added conservatism. The standard error of the mean is a primary variable in the calculation; therefore, the population standard deviation will heavily influence the calculated UCL.

The need for estimating an UCL may serve as the basis for sample planning and the required number of samples. Additionally, the need for estimating a UCL may be secondary to other decisions, such as hypothesis testing. The data assessor should recognize that the width of the confidence interval and hence both lower confidence limits and UTLs may be too broad when the sample data set has a lot of variability and the sample sizes calculated were not adequate (i.e., smaller than necessary). In other words, if the population was inadequately sampled, calculated UCLs may be un-realistically large. The central limit theorem (CLT) states that if sample sizes are sufficiently large, then the calculated sample mean will follow a normal distribution. This is not always the case under typical environmental sampling campaigns, as there are various circumstances that require a prohibitively large sample size for the CLT to be implemented in a UCL calculation. To address the practical limitation of the CLT, UCL calculations are dependent on the underlying sample data distributions. Selecting the appropriate UCL requires consideration and agreement between stakeholders. Generally, UCLs are based on a normal, gamma, log normal, or distribution free (non-parametric) sample distribution. Software such as ProUCL and VSP, have the functionality to examine the data, provide the various UCLs, and recommends which UCL should be considered—all possible calculation variations are too numerous and/or complex to describe here. However, two UCL equations are presented here for populations that are either lognormally or normally distributed.

For a lognormal distribution, the first step is to transform the data using the lateral log function in, for example, a spreadsheet. The UCL is then calculated as follows:

$$UCL = e^{\left(\bar{x}+0.5s^2+sH/\sqrt{n-1}\right)}$$

where,
$\bar{x}$ = the mean of log-transformed data,
s = the standard deviation of the transformed data,
H = the H-statistic (e.g., from Gilbert 1987), and
n = the number of sample/measurements.

For a normal distribution, the UCL is then calculated as follows:

$$UCL = \bar{x} + t\left(s/\sqrt{n}\right)$$

where,
$\bar{x}$ = the mean of untransformed data,
s = the standard deviation of the untransformed data,
t = the student t-statistic (e.g., from Gilbert 1987), and
n = the number of sample/measurements.

The selected UCL is then used in calculating total activity within the decision unit or may be directly compared to an approved $DCGL_V$ to represent the upper bound of a unit activity that if concentrations were less than that value, could not lead to exposures that would exceed the applicable dose limits. The use of a UCL as a compliance parameter is common where chemical contamination is the concern, and potentially applicable to HTDs where scanning is not effective.

The licensee may also consider weighted average concentrations for complex FSSs with multiple SSUs. An example weighted average calculation involves the average concentration in each SSU and the fraction of the total volume represented by each SSU. The equation for this calculation is as follows:

$$W = \frac{\sum_j \bar{x}_j \times V_j}{\sum_j V_j}$$

where,

W = volume weighted average concentration,
$\bar{x}_j$= the average concentration in SSU number j, and
V_j = material volume in SSU number j.

Whatever estimation criterion is established, the licensee will be required to balance the needs of hypothesis test requirements (if applicable) to help ensure all objectives are satisfied.

The software ProUCL was used to examine the example data for the purpose of demonstrating various UCL results and recommends which UCL should be considered for comparison to the applicable $DCGL_V$ (possible calculation variations are too numerous and/or complex to describe here). Example ProUCL outputs for two-sample data sets that were collected to assess Ra-226 concentrations (values are pCi/g) are shown in Figures 2.4 and 2.5. The left tails and medians of both populations were similar, and the presence of outliers in the Figure 2.5 data is clearly reflected in the mean, standard error of the mean, and the resultant UCLs. VSP also has UCL functionality that borrows directly from ProUCL, noting that both software packages can provide a range of estimation statistics, as appropriate for the FSS design.

Sample size calculations can also be performed with both VSP and ProUCL. Required inputs to the sample size calculations include the desired confidence, coverage, desired width of the confidence interval, and the estimated variability in contaminant concentrations. Generally, as any one of these inputs increases, the required sample size increases.

2.4.4. Analytical Approach—Presence/Absence and NTEs (Compliance Strategy)

There may be a scenario where compliance decisions are based on no single location exceeding a $DCGL_W$. Under this scenario, a DCGL essentially becomes a not to exceed (NTE) threshold and assessment of the FSS data via a statistical test of the mean is either inappropriate or insufficient. For example, scanning is not always sufficient for assessing a so-called hard-to-detect (HTD) radionuclide. A licensee can explore the possibility of using a surrogate to estimate HTD concentrations (see MARSSIM Chapter 4), but surrogates are not always reliable (e.g., when concentration ratios between the proposed surrogate and the HTD are unpredictable). If a NTE threshold applies, and neither scanning nor surrogates are effective, then the compliance decision deviates from the traditional MARSSIM paradigm and an alternative analytical approach is needed.

General Statistics			
Total Number of Observations	19	Number of Distinct Observations	19
		Number of Missing Observations	0
Minimum	0.617	Mean	1.366
Maximum	3.569	Median	0.956
SD	0.905	Std. Error of Mean	0.208
Coefficient of Variation	0.663	Skewness	1.6
Assuming Normal Distribution			
95% Normal UCL		**95% UCLs (Adjusted for Skewness)**	
95% Student's-t UCL	1.726	95% Adjusted-CLT UCL (Chen-1995)	1.788
		95% Modified-t UCL (Johnson-1978)	1.738
Assuming Gamma Distribution			
95% Approximate Gamma UCL	1.732	95% Adjusted Gamma UCL	1.769
Assuming Lognormal Distribution			
95% H-UCL	1.738	90% Chebyshev (MVUE) UCL	1.843
95% Chebyshev (MVUE) UCL	2.072	97.5% Chebyshev (MVUE) UCL	2.391
99% Chebyshev (MVUE) UCL	3.018		
Nonparametric Distribution Free UCL Statistics			
Data do not follow a Discernible Distribution			
Nonparametric Distribution Free UCLs			
95% CLT UCL	1.707	95% BCA Bootstrap UCL	1.791
95% Standard Bootstrap UCL	1.706	95% Bootstrap-t UCL	1.922
95% Hall's Bootstrap UCL	1.694	95% Percentile Bootstrap UCL	1.723
90% Chebyshev(Mean, Sd) UCL	1.988	95% Chebyshev(Mean, Sd) UCL	2.27
97.5% Chebyshev(Mean, Sd) UCL	2.662	99% Chebyshev(Mean, Sd) UCL	3.431
Suggested UCL to Use			
95% Student's-t UCL	1.726		

Figure 2.4 Example 1 ProUCL Output—Relatively Low Standard Error

General Statistics			
Total Number of Observations	22	Number of Distinct Observations	21
		Number of Missing Observations	0
Minimum	0.52	Mean	67.07
Maximum	1346	Median	0.85
SD	286.2	Std. Error of Mean	61.01
Coefficient of Variation	4.267	Skewness	4.658
Assuming Normal Distribution			
95% Normal UCL		**95% UCLs (Adjusted for Skewness)**	
95% Student's-t UCL	172.1	95% Adjusted-CLT UCL (Chen-1995)	232.2
		95% Modified-t UCL (Johnson-1978)	182.2
Assuming Gamma Distribution			
95% Approximate Gamma UCL	181	95% Adjusted Gamma UCL	195.9
Assuming Lognormal Distribution			
95% H-UCL	63.4	90% Chebyshev (MVUE) UCL	23.95
95% Chebyshev (MVUE) UCL	30.54	97.5% Chebyshev (MVUE) UCL	39.69
99% Chebyshev (MVUE) UCL	57.67		
Nonparametric Distribution Free UCLs			
95% CLT UCL	167.4	95% BCA Bootstrap UCL	254.6
95% Standard Bootstrap UCL	164.5	95% Bootstrap-t UCL	4143
95% Hall's Bootstrap UCL	4136	95% Percentile Bootstrap UCL	188.3
90% Chebyshev(Mean, Sd) UCL	250.1	95% Chebyshev(Mean, Sd) UCL	333
97.5% Chebyshev(Mean, Sd) UCL	448.1	99% Chebyshev(Mean, Sd) UCL	674.2
Suggested UCL to Use			
95% Student's-t UCL	172.1		

Figure 2.5 Example 2 ProUCL Output— Relatively High Standard Error

The FSS goal for NTE threshold testing is to demonstrate that a high percentage of the SSU is below the NTE at a specified level of confidence. The technical term for this type of statistical assessment is compliance (or presence/absence) sampling. Under the compliance sampling paradigm, the SSU is divided into equally sized grid cells. A statistically determined number of grid cells are investigated and categorized with a binary decision—acceptable or unacceptable. The collective outcome of all grid cells is then used to assess whether the null hypothesis can be rejected. Hypotheses are stated as follows:

> H_0 : The true number of unacceptable grid cells (D) is greater than the largest tolerated number of unacceptable grid cells (D_0), mathematically: $D > D_0$,
>
> H_A : The true number of unacceptable grid cells (D) is less than or equal to the largest tolerated number of unacceptable grid cells, mathematically: $D \leq D_0$.

Data collected for this type of compliance testing will augment a population mean/median assessment (i.e., when multiple decisions are needed). In other words, a presence/absence analytical approach should be considered for decision units involving an NTE; or where both the average concentration is assessed against the $DCGL_{W,}$ and elevated areas of concern are identified. A presence/absence approach can supplement inventory estimates where scanning for elevated areas cannot be physically performed or scanning is not relevant based on the ROCs (e.g., HTD radionuclides in soil without a gamma emitting surrogate). Furthermore, because the required presence/absence sample size will likely exceed those of the Sign or WRS test in most cases, using all sample results in the Sign or WRS test assessment will have the added benefit of increased power.

There are several variations of the presence/absence survey design that account for false positive/false negative allowances, probability of encountering an elevated area of concern, and include or exclude targeted grid cell sampling. Note that if grid failures are allowed, the number of acceptable grid cells should be determined during the planning phase. Planning inputs include the percentage of the SSU that can be unacceptable (i.e., exceed the DCGL), desired confidence, SSU area, and the grid cell size. The probability or proportion (e.g., 100 percent of the decision unit needs to be acceptable) is specified at a given confidence, generally between 90 and 99 percent confidence. The first step of survey design is to specify a total number of grid cells—a defined population of independent items within the decision unit—that may be independently sampled. In the case of SSU these grid cells may be a unit area or volume. A non-trivial component of designing a presence/absence sampling approach is determining the appropriate grid cell size. One approach may be to set the grid cell size equal to an elevated area size of concern based on EMC for a nominal FSS sample spacing. The DQO process with input from stakeholders is followed to define the size or volume of the cells.

As an example, consider a basement structural decision unit planned for investigation by in situ gamma spectrometry. The grid cells making up the population from which the specific measurement locations are randomly selected may equate to the area of the detector field of view (FOV). The number of required grid cells investigated are dependent on the desired confidence and percentage of allowable failures. The random grid cells are measured and are categorized as above or below the threshold (i.e., pass or fail). If the number of grid failures is less than the acceptable number, the licensee will reject the null hypothesis. Visual Sample Plan provides both planning and assessment modules for presence/absence survey design related to the following:

- Determining whether an unacceptable proportion of the target population exceeds a threshold,
- Discovery sampling (discover unacceptable grid cells),
- Determining the required number of measurements for a desired confidence level, and
- Calculating the confidence level based on the number of measurements already collected.

2.4.5. Analytical Approach—EMCs

SSUs logistics can create issues on schedule, health and safety, and other factors that may necessitate some relief to the standard FSS process guidance. For instance, if an excavation cannot remain open for an extended period to allow for the receipt and evaluation of laboratory analytical results and to permit regulatory inspections, then the licensee should expect to provide additional information that provides confidence that elevated areas are no longer present. This might require 100 percent scanning and liberal judgmental sampling when gamma emitters are present as an ROC and serve as a surrogate to the other ROCs and/or implementing a more rigorous sample number beyond what MARSSIM planning might recommend. Similarly, if an SSU cannot be adequately accessed for scanning or ROCs do not include gamma emitters, the licensee should also consider a more rigorous sampling campaign during the FSS. SSUs that are not readily accessible for scanning but that can remain open until analytical data are received, and outliers can be evaluated via retrospective methods, might be candidates for maintaining a typical MARSSIM sample size type with less stringent scanning although MARSSIM suggested scanning percentages are still encouraged for accessible portions as a good practice. Systematic sample data above the $DCGL_{W(or\ V)}$ are examined for outliers, where the outlier threshold is established through DQOs, for example concentrations beyond the upper percentiles of the specific SSU population results or other factors.

Scanning relief for difficult to assess SSUs may be acceptable for small, elevated areas in the subsurface where the dominant dose pathway is direct exposure (e.g., Cs-137 and Co-60), because direct exposure becomes less important in the subsurface. However, if the material is brought to the surface, the direct exposure pathway becomes more important. The requirements for scanning and development of $DCGL_{EMC}$ values, or more broadly the necessity for identifying areas of elevated contamination that may exist between sampling locations, are to be addressed during DQO development. To summarize, the alternatives to scanning and increasing sampling density if required scan MDCs are not achievable or scanning is not achievable due to the presence of only HTDs in soil include:

- Prospective sampling designed to satisfy a defined probability of hitting an elevated area of a predetermined size, use of composite sampling, or other methods for enhanced elevated area detection probability,
- Retrospective outlier evaluations to identify locations that potentially exceed the upper bound/percentile of the population distribution illustrated in box plots or other outlier tests,
- Additional statistical parameter assessment such as the use of an UCL95, threshold values, or predictive calculation (Chebyshev's) etc., to determine a concentration that if exceeded represents an elevated area requiring further investigation, and
- Additional sampling to better resolve the size, concentrations, and impact to potential future dose from the elevated area in combination with the estimated concentration/inventory within the decision unit. Two-stage sampling as described in Appendix C in NUREG-1757, Volume 2, Rev. 2, is an example that could be considered.

2.5 Number of Samples

Having selected the analytical method and decision errors, the licensee can now calculate the number of samples to collected per decision unit (*N*). As is the common theme throughout this guidance, the MARSSIM may not be directly applicable to subsurface investigations, although the guidance may still be appropriate for many SSUs. For example, the WRS or Sign test may be selected for large SSUs—when selecting Scenario A—thus the licensee will calculate *N* using MARSSIM Tables 5.3 (WRS) and 5.5 (Sign) or can perform hand calculations. These hand calculations are summarized as follows in NUREG-1757.

Number of Samples Needed for Scenario A—Wilcoxon Rank Sum Test. The minimum number of samples, *N*, needed in each decision unit for the WRS test may be determined from Equation 2.1 (adapted from MARSSIM Equation 5-1 with N redefined as the number of samples in the SSU):

Eq. 2.1 $$N = \frac{1}{2} \times \frac{\left(Z_{1-\alpha} + Z_{1-\beta}\right)^2}{3(P_r - 0.5)^2}$$

where N = the number of samples in the SSU
$Z_{1-\alpha}$ = the percentile represented by the decision error α
$Z_{1-\beta}$ = the percentile represented by the decision error β
P_r = the probability that a random measurement from the SSU exceeds a random measurement from the background reference area by less than the $DCGL_{W\ (or\ V)}$ when the SSU median is equal to the LBGR (e.g., the expected mean) concentration above background
½ = a factor added to MARSSIM Equation 5-1 because N is defined in this guide as the number of samples in the SSU (the same number of samples would be taken in the reference area)

Tables 5.1 and 5.2 of MARSSIM contain values of P_r, $Z_{1-\alpha}$, and $Z_{1-\beta}$, with P_r based on the relative shift (Δ/σ) (i.e., it does not need to be calculated or specified). N is the minimum number of samples necessary in each SSU. An additional N samples will also be needed in the reference area. If N is not an integer, the number of samples is determined by rounding up. In addition, the licensee should consider taking some additional samples (MARSSIM recommends 20 percent) to protect against the possibility of lost or unusable data. Fewer samples increase the probability of an acceptable decision unit failing to demonstrate compliance with the radiological criteria for release.

Number of Samples Needed for Scenario A—Sign Test. The number of samples N needed in a decision unit for the Sign test may be determined from Equation 2.2 (adapted from MARSSIM Equation 5-2 with N redefined as the number of samples in the SSU):

Eq. 2.2 $$N = \frac{\left(Z_{1-\alpha} + Z_{1-\beta}\right)^2}{4(Sign\,p - 0.5)^2}$$

where N = the number of samples in the SSU
$Z_{1-\alpha}$ = the percentile represented by the decision error α
$Z_{1-\beta}$ = the percentile represented by the decision error β
Sign p = estimated probability that a random measurement for the SSU will be less than the $DCGL_{W\ (or\ V)}$ when the SSU median concentration is actually at the LBGR

Tables 5.2 and 5.4 of MARSSIM contain the values of $Z_{1-\alpha}$, $Z_{1-\beta}$, and *Sign p*, recalling that the value for *Sign p* is selected based on the relative shift (Δ/σ). In addition, the licensee should consider taking some additional samples (MARSSIM recommends 20 percent) to protect against the possibility of lost or unusable data. Fewer samples increase the probability of an acceptable decision unit failing to demonstrate compliance with the radiological criteria for release. If a decision unit fails to demonstrate compliance because there were not enough samples taken, a totally new sampling effort may be needed unless resampling was anticipated.

Number of Samples Needed for Scenario B and B'. Unfortunately, there is not a simple approach for addressing Scenario B and B', which a licensee could, for example, use when selecting a reuse/borrow area. Licensees are responsible for selecting the best test based on site-specific conditions and stakeholder input. However, a simplified approach is presented here as an example method for calculating N in this guidance. For additional details, licensees can consult the ProUCL Technical Guide (EPA 2015). This guide also discusses calculating N when the WRS or Sign test is selected under Scenario A, per the MARSSIM approach.

Two methods for calculating N are presented, one when selecting the parametric Two-sample t-test and one when selecting the non-parametric WMW test. The former is only appropriate under certain conditions but generally results in higher power, although the latter simplifies the process because it is non-parametric. The choices are these:

1. Calculate N using the t-test approach to gain power (relative to WMW), then retrospectively test the data to determine if the underlying conditions required for the t-test are present. If present, use the t-test and if not, use the WMW test.
2. Calculate N using the WMW approach and take advantage on the non-parametric design—this is like the MARSSIM approach.

The underlying conditions for the t-test are as follows: First, both populations (e.g., representing the reuse/borrow area and the reference area) should be normally distributed. Second, the variances for both populations should be the same, within statistical tolerances. If this is or is presumed the case, then the next step is to select delta (Δ), or the width of the gray region like that used in MARSSIM Scenario A. However, in MARSSIM Scenario A the gray region is the DCGL – LBGR (or typically the DCGL minus the expected mean concentration). There is no default rule for setting Δ for the t-test, so the licensee will have to set Δ during DQO development. Having met these requirements and selected Δ, N is calculated using Equation 2.3, as follows:

Eq. 2.3
$$N = 2\left(Z_{1-\alpha} + Z_{1-\beta}\right)^2\left(\frac{\sigma_p}{\Delta}\right)^2 + \left(\frac{Z_{1-\alpha}{}^2}{4}\right)$$

where N = the number of samples in the SSU

$Z_{1-\alpha}$ = the percentile represented by the decision error α

$Z_{1-\beta}$ = the percentile represented by the decision error β

σ_p = the estimated pooled standard deviation of the two populations

Δ = width of the gray region (e.g., difference between population means)

If preliminary characterization data are available, the pooled standard deviation is calculated by:

Eq. 2.4
$$\sigma_p = \sqrt{\frac{(n-1)\sigma_{SSU}^2 \ + \ (m-1)\sigma_R^2}{(m-1)+(n-1)}}$$

where σ_p = pooled standard deviation of the SSU and background reference area

σ_{SSU} = the percentile represented by the decision error α

σ_R = the percentile represented by the decision error β

n = number of samples from the SSU

m = number of samples from the background reference area

Using this approach, N statistical samples will be collected from the reuse/borrow site, and N statistical samples will be collected in the reference area.

If the licensee chooses to start with a non-parametric approach (i.e., does not intend to retrospectively test to determine if the t-test can apply), then N can be calculated using Equation 2.5, as follows:

Eq. 2.5
$$N = 1.16\left[2\left(Z_{1-\alpha} + Z_{1-\beta}\right)^2\left(\frac{\sigma_p}{\Delta}\right)^2 + \left(\frac{Z_{1-\alpha}{}^2}{4}\right)\right]$$

where N = the number of samples in the SSU

$Z_{1-\alpha}$ = the percentile represented by the decision error α

$Z_{1-\beta}$ = the percentile represented by the decision error β

σ = the estimated pooled standard deviation of the two populations

Δ = width of the gray region (e.g., difference between population means)

Note that Equations 2.3 and 2.5 are the same except for the addition of the 1.16 multiplier for the WMW approach. This is like the 1.2 multiplier (20 percent) used in MARSSIM to account for lost or unusable samples.

Number of Samples for Estimation Problems. If the objective is to estimate the mean, as may be required for an estimation problem, multiple methods may be considered. A commonly used formula is as follows:

Eq. 2.6 $$N = \sigma^2 Z^2{}_{1-(\alpha/2)} \;/\; \Delta^2$$

where N = the number of samples in the SSU

$Z_{1-(\alpha/2)}$ = the percentile represented by the decision error α

σ = the estimated standard deviation of the decision unit concentration

Δ = width of the gray region (in this case, the tolerance/error on the estimation of the mean)

As an alternative, Equation 2.7 may be used with a t-distribution based equation:

Eq. 2.7 $$N = \sigma^2 t^2{}_{(n-1),(\alpha/2)} \;/\; \Delta^2$$

where N = the number of samples in the SSU

$t_{(n-1),(1-\alpha/2)}$ = t-critical value with (n-1) degrees of freedom

σ = the estimated standard deviation of the decision unit concentration

Δ = width of the gray region (in this case, the tolerance/error on the estimation of the mean)

If the choice is unclear and a minimum sample size is needed to estimate the mean for a specified confidence (1-α) and margin of error (Δ), Equation 2.8 may be used.

Eq. 2.8 $$N = \sigma^2 Z^2{}_{1-(\alpha/2)} \;/\; \Delta^2 + Z^2{}_{1-(\alpha/2)} \;/\; 2$$

It is worth noting that MARSSIM practitioners often use software packages such as ProUCL, which defaults to Equation 2.8 when estimating the mean for a given confidence and error.

Finally, computation of parameters such as the UCL depend upon three values: the sample mean, sample variability (standard deviation) and a critical value. Critical value depends upon sample size, data distribution, and confidence level. For samples of small size (< 8-10), the critical values are large and unstable, and UCLs based upon a data set with fewer than 8-10 observations are mainly driven by those critical values. The differences in the corresponding critical values tend to stabilize when the sample size becomes larger than 8-10. For this reason, licensees should consider setting the minimum sample size to 10 when calculating a UCL as practical boundary condition (DQO Step 4). This is analogous to setting the relative shift to 1 under Scenario A.

Number of Samples for a Small Decision Unit. There may be cases when the subsurface decision unit is small compared to the scale of traditional SUs (e.g., much smaller, less than 10 percent, of the 2,000 m^2 or 10,000 m^2 baselines), or small compared to the area used to derive DCGLs. An example may be an excavation created by removing a relatively small underground tank that for industrial safety reasons, should be backfilled prior to a FSS of the survey unit in which it is located. Like characterization of elevations within a survey unit, there is no standard approach for dealing with these small decision units (SDUs), and the licensee should use the DQO process to ensure the right type, quantity, and quality of data are collected to make FSS decisions. The licensee may consider, for example, if small areas represent a decision problem (requiring a statistical test) or an estimation problem (estimate the average or maximum value).

It may seem unreasonable to distribute the same number of *N* statistical samples in both small SDU and a baseline unit SU/SSU. It may also be unclear specifically when an SDU is too small to follow the traditional approach, or alternatively, when the sample density is too high. The licensee should develop a strategy that answers the following two questions:

1. When is a decision unit too small for statistical sampling?
2. What is the sample strategy if statistical sampling is not used?

Regarding Question 1, there is no simple answer. The licensee can present, for example, practical boundaries during DQO development (specifically DQO Step 4) if SDUs are anticipated. The licensee can set practical boundaries at some fraction of the baseline SU/SSU, at some dose-based threshold (e.g., based on EMC), or at some other threshold that addresses site-specific conditions. For example, a hypothetical project develops $DCGL_{EMC}$ concentrations, and the survey planner notices that values start to increase exponentially for areas below 300 m^2. This is an indication that some exposure pathways (like inhalation and ingestion) are less impactful as the area of residual radioactivity decreases. The project decides to set a practical boundary at 300 m^2, meaning any SDU of 300 m^2 or less is too small for statistical sampling and it is more appropriate to treat the SDUs as potentially elevated areas. A licensee may use other thresholds or professional judgment, which should be documented in the decommissioning plan (DP).

Regarding Question 2, again there is no simple answer. For example, the licensee may be tempted to scale the *N* statistical samples based on the ratio between the SDU area and baseline area. This is not, however, a valid approach given a statistical sample number is calculated for a specific purpose (e.g., to perform a statistical test of stated confidence), and reducing the number arbitrarily or out of convenience undermines the original purpose of calculating *N*. To determine the appropriate number of samples for a small decision unit, the licensee will need to establish a decision rule, considering the following:

- The parameter of interest for making decisions about the target population
    - Is it more important, for example, to estimate the mean concentration (for comparison to DCGLs) or maximum concentrations (for comparison to an EMC or NTE criterion)?
- The action level that causes a decision maker to choose between the alternative actions.
    - Example action levels are DCGLs, $DCGL_{EMC}$, and NTE criteria.
- Alternative actions that could result from the decision.
    - Example alternative actions include remediation, composite sampling, or other actions.

The licensee may conclude that judgmental or composite sampling is sufficient for some small excavations or basement structures. For a design that relies on judgmental sampling, scanning can be used to locate the area(s) of highest radioactivity, which is sampled, then the associated results are directly compared to action levels. For a design that relies on composite sampling, composites may be used to estimate average concentration which are compared to modified action levels (action levels that are typically divided by the number of samples utilized to establish the composite sample). If the composite exceeds the modified action level, the licensee should decide whether to analyze each individual sample, remediate, or perform some other action. Regardless of the selected design, the approach for SDUs should be developed using DQO process based on site-specific conditions.

The last issue that the DQOs should address is how to assess the dose associated with residual radioactivity that is detected in the SDU. Residual radioactivity in a SDU may be evaluated like elevated areas in that there is a potential dose to a future site user. A sum of fractions (SOF) value for the SDU can be generated and conservatively added to the SOF for the survey unit in which it is located and discussed in the survey unit final status survey report (FSSR). Alternative means of addressing potential exposure associated with a SDU should be discussed, and agreed upon, with the regulator.

2.6 Scanning and Direct Measurement of Subsurface Media

Consistent with the MARSSIM method, the analytical approach specifies that sample data are required for direct comparison to DCGLs. Scanning is used to supplement the survey by confirming the classification and identifying elevated concentrations of residual radioactivity that may not be identified by randomized sampling. The following presents guidelines for the degree of scanning (also known as “percent coverage”) and instrumentation that licensees may use to perform the scans. Licensees may also review NUREG-1507 (NRC 2020a), NUREG-1761 (NRC 2002), and MARSSIM (NRC 2000) for additional information on scanning instrumentation, including calculating the scan MDC. MARSSIM Appendix H, for example, describes a wide range of radiation detectors and application.

2.6.1. Degree of Scanning

For this discussion the degree of scanning is divided into two categories: SSUs and reuse/borrow scenarios. This division assumes that the FSS for SSUs will, to the extent practicable, follow a MARSSIM-like approach. Reuse or borrow materials may also be subject to a MARSSIM-like approach, or site-specific requirements for these materials may necessitate separate DQOs, different statistical requirements, etc. That is, the MAC for reuse/borrow, which will be placed on top of or in an SSU, may be different than criteria for the SSU itself—these potential differences are discussed here in the context of scanning.

Degree of SSU Scanning. Regarding the degree of scanning, existing MARSSIM guidance for surface SUs is likely sufficient for most SSUs. Scan coverage for subsurface soil and structure SSUs is, therefore, based on class and accessibility:

Class 1: 100 % survey of accessible surfaces

Class 2: from 10-100 % of accessible surfaces (percentage based on professional judgment), or determined quantitatively using the following equation:

Eq. 2.9 $$\% \text{ scan} = 100 \times \frac{\left(10 - \frac{\Delta}{\sigma}\right)}{10}$$

where Δ/σ is the relative shift, as described in MARSSIM Chapter 5.

Class 3: percentage is based on professional judgment.

For any selected Class 2 and Class 3 SSU, the license should consider accessible/inaccessible fractions when planning the FSS. For example, if 50 percent coverage is planned in a Class 2 SSU, but only 50 percent of the SSU is safely accessible (e.g., above the waterline, etc.), then the licensee should compensate for the lack of scan data. Possible options include, but are not limited to, increasing the sample density where scanning is impossible or unsafe, or collecting composite in addition to or instead of discrete samples. By compensating for the lack of planned scan data, the licensee helps ensure classification designations are correct, elevated areas are identified, and better decisions are possible even when scanning is limited.

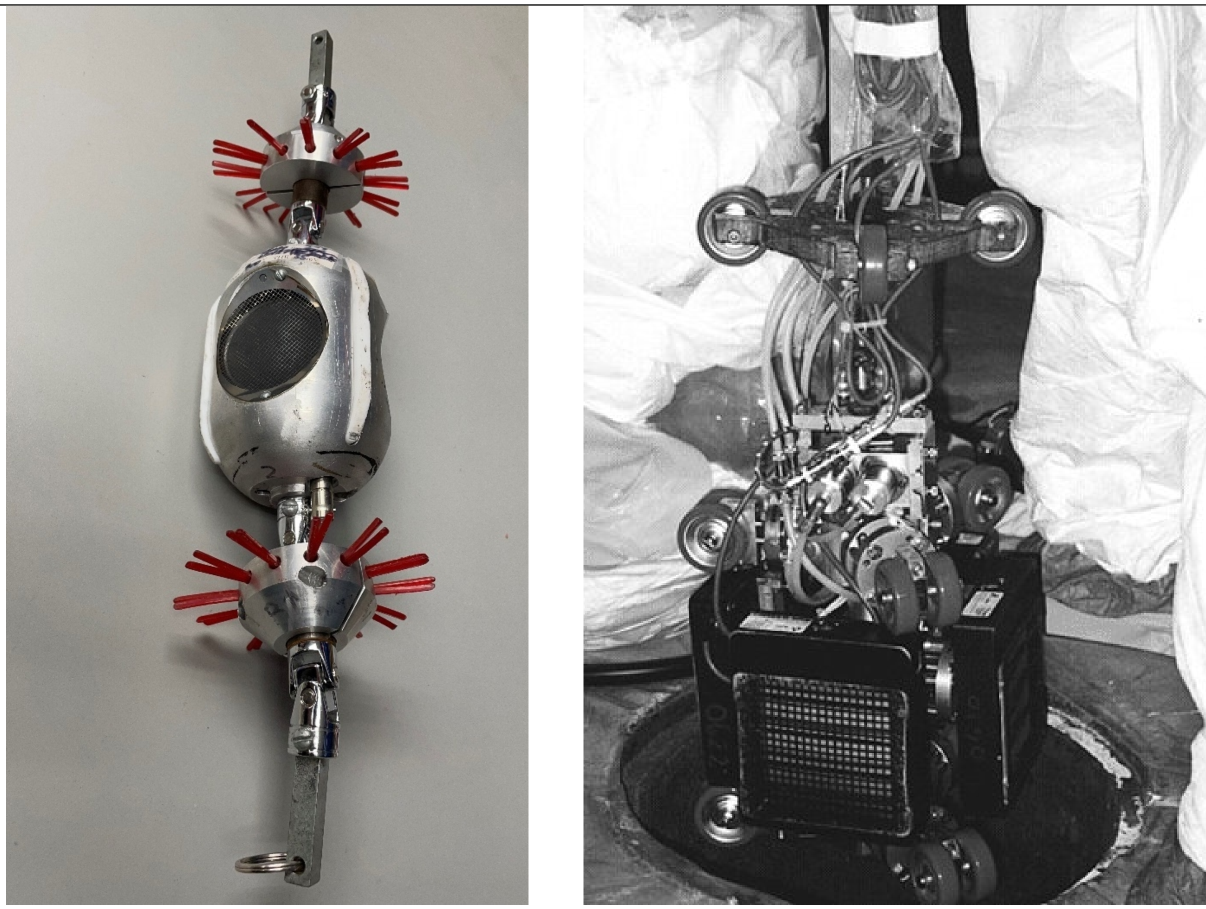
Recall that the main function of scanning in the context of MARSSIM is that scanning is a tool to identify dose-significant elevated areas that are unlikely to be identified by sampling alone. In some cases, when the scan MDC is greater than the DCGL, the sample density is increased until the $DCGL_{EMC}$ (representing a specific area per sample) is equivalent to the scan MDC. This increase is less important in SSUs, because the subsurface dose model involves indirect exposure pathways (i.e., requires excavation, mixing, leaching, etc. to facilitate the exposure). Therefore, it is less likely that dose-significant elevated area concentrations in an SSU will go undiscovered by standard sampling and scanning methods. The licensee is still obligated to identify inaccessible residual radioactivity within a given SSU such as sumps, embedded pipes, steep slopes, and subgrade soils. Scanning percentages for these potential sources via remote methods are addressed on a case-by-case basis, although examples include the following:

- Pipe crawlers in embedded piping,
- Boreholes using Geoprobe® or similar methods to identify sub-slab materials, and
- Mounted NaI or HPGe detector to scan sheer walls or confined spaces.

Embedded piping may be particularly difficult to scan during an FSS effort given conventional survey techniques are unlikely to access the pipe interiors. Embedded pipes may become contaminated because of their function of transporting radioactive liquids or gases. Process piping, such as that associated with nuclear power reactor systems, can be embedded in concrete, which further complicates the assessment. In addition, the small diameter of embedded piping typically makes it extremely difficult to access the interior surfaces. Dismantling portions of the surrounding structure might be required to gain access to internal surfaces. Small detectors, such as miniature GM detectors, and other “pipe crawling” detector systems, such as those illustrated in Figure 2.6, have been used to assess surface contamination in pipe systems. If embedded piping cannot be characterized in situ to collect the data required for compliance testing, the licensee may be required to explore alternative actions such as complete removal, grouting in place, or other options, as appropriate.

The licensee should also follow existing guidance such as MARSSIM (NRC 2000) and NUREG-1507 (NRC 2020a) for selecting detectors and establishing scan MDCs to ensure scanning equipment and techniques are optimized. In any case, scan MDC is determined by considering instrumentation, scan protocols, contaminant geometry, radiation quality (i.e., type, energy, and yield), and other factors as described in MARSSIM and NUREG-1507.

When volumetric samples are collected during the FSS, it is also a good practice to, when possible, scan or otherwise measure radiation levels within the hole left after sample extraction. It is likely that radiation levels will increase by a modest percentage (e.g., 10-20 percent) due to source geometry. However, radiation levels are not expected to increase by large percentages due to geometry alone. It is possible that the contamination increases with depth, and an additional measurement represents a simple and inexpensive means to minimize decision errors. The additional measurement can also be used to prove/disprove remedial effectiveness and pre-FSS assumptions.



small diameter crawler large diameter crawler

Figure 2.6 Example Pipe Crawlers

The width and depth of the borehole may vary depending on whether the purpose is to collect a relatively shallow sample for laboratory analysis or a relatively deep Geoprobe core to investigate the potential for ROC leaching and migration. Borehole scanning effectiveness is likely limited to gamma emitting ROCs and NaI(Tl) or CsI(Tl) detectors, but licensees can use this data to help locate lenses of contamination (e.g., for judgmental sampling), verify the presence/absence of contamination, bound known contamination plumes, and produce other real-time data for making better decisions. Depending on the nature of extracted materials, the core can also be scanned ex situ using a variety of beta/gamma detectors. That is, down-hole scan is used to identify gamma emitting ROCs at or near the borehole wall, and core scan is used to identify beta/gamma emitting ROCs from the extracted materials. Unless physically impossible (e.g., borehole collapses), 100 percent scan of both the borehole and extracted core is ideal.

Degree of Reuse and Borrow Media Scanning. Onsite materials targeted for reuse may have been subject to either MARSSIM or MARSAME surveys depending on the FSS design. For example, a licensee targets a Class 2 land area as an onsite borrow site after the area meets all objectives of a MARSSIM-based FSS. If the FSS confirms that the classification is correct and little or no contamination is identified, the soils from the SU can be used as excavation or substructure backfill and the degree of scanning for the Class 2 area, as defined by the LTP, is sufficient. It is important to note that the added risk from the reused materials would need to be considered as part of the demonstration of compliance with the release criteria, and that the $DCGL_V$ may differ from the $DCGL_W$ used for assigning the Class 2 designation and would therefore, constitute a reason why additional survey of the borrow material may be needed prior to reuse. MARSAME may be used to make disposition decisions for an excess building with a history of radiological activities. As with the soil SU, if the MARSAME-method is sufficient for making an off-site disposition decision, then MARSAME-like methods should be sufficient to evaluate the reuse and borrow MAC. The underlying principle is as follows:

> If MARSSIM/MARSAME-based methods are sufficient for the release or off-site disposition of impacted materials, the same methods should be sufficient for evaluating materials as potential excavation of structural backfill.

There is, however, the potential that false negative decision errors were made because of limited characterization and FSS activities—only 100 percent sampling can eliminate decision errors. NUREG-1757 Vol. 2, Appendix G acknowledges this possibility by stating, "…if the entire depth of reuse soil cannot be adequately surveyed it may be necessary to excavate and survey soil via lift depths consistent with surface soil dose modeling and instrument capabilities." The degree of scanning is not explicitly stated, although 100 percent of all materials can be implied. Because the degree of scanning should relate to the potential for exceeding criteria, arguments can be presented on why less than 100 percent scanning may be acceptable.

Good practices apply to MAC, such as including reuse materials in a licensee's quality assurance (QA) program. The approach is not dissimilar to that of an analytical laboratory or radiological instrument shop—routine/periodic checks demonstrate that the quality objective established at the beginning of a project are maintained throughout. A laboratory will analyze blank, spike, and duplicate samples per batch; and an instrument shop will perform initial quality control (QC) plus daily background and source checks—both are examples of ensuring the associated data are consistent, reliable, and defensible. The same approach can also be applied to reuse materials to ensure that the original assumptions (e.g., class, variability, etc.) are consistent and within tolerances throughout backfill operations. Consider the following as an example program for evaluating soil for reuse:

> A licensee identified a Class 2 SU that, based on a MARSSIM-based FSS, meets the MAC for reuse as backfill for a large basement structure. Project planners have determined it will take over 50 truckloads to complete backfill operations. Although the SU has been demonstrated to statistically satisfy $DCGL_W$ requirements and was demonstrated to meet the definition of a Class 2 area, the licensee includes backfill operations in the project's overall QA program. As part of the program, the licensee scans the contents of set percentage of truckloads taken from the Class 2 SU (e.g., 5-10 percent) and collects samples when detector responses exceed investigation levels. When samples are collected, results are compared to the thresholds set during

the DQO process. By performing periodic scans and collecting samples per the QA program, the licensee quantifiably demonstrates that reuse materials meet (or do not meet) MAC until the end of backfilling operations.

Although Class 2 and Class 3 materials may seem to be more suitable for reuse/backfill, Class 1 materials may also be used. The licensee should weigh the risk of exceeding MAC against the benefits of using Class 1 material. This risk could include the potential for elevated pockets of radioactivity that make materials less desirable (i.e., backfill is not a convenient and inexpensive equivalent to off-site disposal). Overall, however, the same percentages as SU and SSU scanning can also be applied to reuse materials—see Equation 2.9.

NUREG-1757 Volume 2, Appendix G discusses options for scanning soil targeted for reuse, including scanning each lift in situ prior to extraction and stockpiling, scanning soil lifts ex situ in a laydown area, and using conveyor and sorting systems to scan materials using automation. In any case, DQOs should address scanning processes to help ensure the right type, quality, and quantity of data are collected from reuse materials prior to backfilling.

Off-site borrow sources are likely categorized as non-impacted, so would not fall under any class-specific guideline. The licensee is, therefore, required to determine if a MARSSIM/ MARSAME-like approach is appropriate or some other process is necessary to establish off-site borrow MAC. These MAC are necessary to verify the borrow site has not been unacceptably impacted by site operations or by operations from other unaffiliated sites that could also deposit radiological materials (e.g., naturally occurring radioactive materials from a coal-fired plant).

Although the LTP will specify percent scan coverage, the licensee is still required to select the equipment and protocols for performing the scans of borrow materials. Possible scanning systems used to screen bulk materials can include, but are not limited to, the following:

- Conveyor system
- Portal monitor
- Traditional scanning (e.g., per NUREG-1507 methods)

As with scanning onsite materials targeted for reuse, the licensee should evaluate the limits of detection by considering scan speed, medium thickness, radiation quality, and other parameters that relate to detectability. For example, a licensee may lay materials in an approximately 6 in (15 cm) layer[1] and have surveyors scan for elevated areas. This is only acceptable assuming the project's scan MDC was derived using, for example, the likely contaminant geometry. Similarly, licensees should demonstrate conveyor systems, portal monitors, etc. can achieve scan requirements—just because materials pass through a conveyor/monitoring system does not mean the system can detect ROCs at an investigation level.

2.6.2. In Situ Gamma Spectrometry with Scanning or In Lieu of Scanning

Traditional surface scan methods may be supplemented or replaced, in part or in whole, by the collection of in situ gamma spectrometry (ISGS) measurements using a high-purity germanium (HPGe) or similar solid-state detector. Generally, these measurements are performed with a collimated detector that restricts the FOV to a circular geometry. Restricting the FOV eliminates the influence of nearby gamma sources on the detector response, thereby simplifying the

[1] A thicker layer of soil could be justified as part of the DQO process.

calibration model. The FOV area is dependent on the collimator size/shape and surface to detector distance (also known as the stand-off distance). Several shapes/sizes of collimators are commercially available, however, a circular collimator with either a 30-degree or 90-degree opening is common for decommissioning applications. For example, the FOV diameter (FOV_d) is approximately twice the stand-off distance for a 90-degree circular collimator. To achieve 100 percent coverage using a circular collimator, the licensee should account for the “missed” surface area from spacing the center point of the measurements equal to the FOV_d. Figure 2.7A illustrates the coverage of ISGS measurements spaced at a distance (d) or twice the radium (2r) (i.e., d = 2r = FOV_d). The packing density, η, is the ratio of the area covered by all the measurements to the total area of surface. The measurement layout in Figure 2.7A results in a packing density less than 1. Although, not formally derived in this document, the adjusted measurement spacing (d’) such that 100 percent of the surface is covered by the measurement is given by: $d' = 3r/\sqrt{3}$. Figure 2.7B depicts the adjusted measurement spacing; note that for the adjusted spacing η is greater than 1. Adjusting the measurement spacing increases the number of samples relative to the required number for the purposes of the statistical test, which is the compromise for using an exclusively in situ measurement regime. The degree to which the required number of in situ measurements oversamples the SSU (relative to the requirements for the statistical test) depends on the detector stand-off distance and SSU area; an increase in sample size by a factor of four or more is not uncommon.

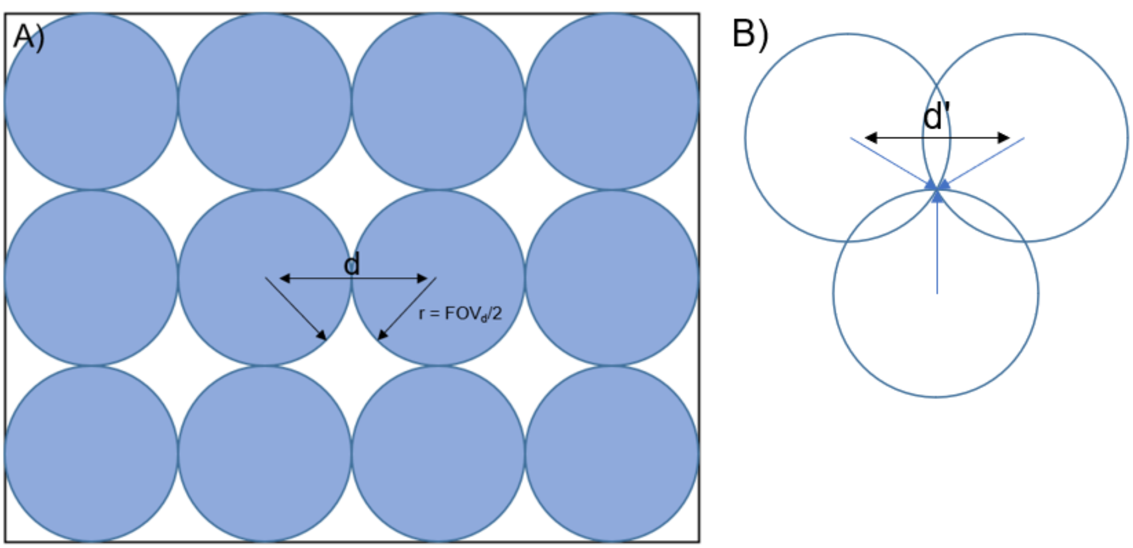


Figure 2.7 A) Illustration of Non-overlapping In Situ Measurements, and B) Adjusted Measurement Spacing Achieving 100 Percent Surface Coverage.

Achieving 100 percent measurement coverage is inefficient, as portions of the surface are essentially measured twice. Therefore, the licensee may choose to optimize the survey design by collecting a combination of statistical measurements (using a relatively long acquisition time) and “scanning” measurements (using a relatively short acquisition time). The statistical measurements are intended to satisfy measurement quality objectives (MQOs) related to subsequent statistical inferences, whereas the scanning measurements are intended to locate discrete areas of radioactivity—elevated areas above investigation levels may be subject to judgmental measurements with long acquisition time. Assessing the concentration of an elevated area identified by scanning may be accomplished with the in situ system. If the area of the hot spot is estimated, the detector stand-off distance can be adjusted such that the measurement FOV area corresponds to the hot spot size (i.e., the measurement result will represent the hot spot concentration). These statistical versus scanning measurements differ only in the spectrum acquisition time—and as a result, the MDCs. For example, 30 statistical measurements may be collected with a spectrum acquisition time of 15 minutes, sufficient, to achieve an MDC less than 10 percent of the $DCGL_V$; and an additional 80 “scanning” measurements may be collected with and acquisition time of 5 minute to achieve an MDC less than a pre-defined investigation level (e.g., like a $DCGL_{EMC}$ under MARSSIM). Careful consideration should be given to the MDCs because a reduced acquisition time should still ensure applicable MQOs are satisfied.

In Situ Measurement Coverage. As with traditional scanning methods, suggested in situ measurement coverage for subsurface soil and structure SSUs is based on the traditional approach considering class and accessibility:

Class 1: 100% survey of accessible surfaces (i.e., $\eta \geq 1.0$)

Class 2: from 10-100% of accessible surfaces (percentage based on professional judgment), or determine quantitatively as follows, using the same approach described in Section 2.6.1:

$$\% \text{ scan} = 100 \times \frac{\left(10 - \frac{\Delta}{\sigma}\right)}{10}$$

Measurements are laid out in a random/start systematic patter, as recommended for traditional FSS samples per MARSSIM (Chapter 5) design.

Class 3: percentage is dictated based on the number statistically driven samples, either laid out in a random or systematic fashion.

A typical in situ measurement system will include a mobile cart or other mechanism for mounting the detector and moving the system to each measurement location. The ground-based cart is impractical for measuring raised (i.e., about floor-level) surfaces. The licensee should consider implementing a detector mount that can be positioned using a mobile crane or other appropriate equipment. Due to the sensitive nature of the detector and associated electronics, great care should be taken not to damage the detector when traversing to the next measurement location. Best practice would be to establish a local area network, such that the controller device can communicate with the detector electronics without physical cables.

The detector cannot determine from where in the FOV an individual photon originates, as such measurements of these types will “average out” the activity associated with an elevated area over the FOV. Licensees, therefore, should consider the dose significance, if any, of an individual elevated area smaller than the detector FOV. If determined important, surface scans using traditional hand-held instrumentation may be necessary. Alternatively, the licensee may develop an investigation level for the gamma spectrometry system that corresponds to the response of an elevated area of concern. If it is determined that elevated areas are of concern and an appropriate in situ investigation level cannot be developed, separate surface scans with hand-held portable instrumentation should be performed.

2.6.3. Subsurface FSS Instrumentation

The methods applied and instrumentation recommended for radiological investigations are independent from the classification of the decision unit—classification only affects the coverage requirements, not the type of instrumentation (detectors). As with MARSSIM for surface soil, the default guidance position where detectable gamma emissions are associated with the ROCs is that the subsurface excavation floors and walls (soil/bedrock) and basement structures (walls/slabs) will be subject to some qualitative gamma scanning coverage, combined with judgmental sampling of locations or sub-population of locations exhibiting elevated gamma radiation counts. The decision to perform direct scanning for alpha and/or beta emitters, with or without comingled gamma emitting ROCs, and the scan coverage on structural subsurface or bedrock decision units should be an output of the DQO process and knowledge of the contamination profile and distribution within the media being investigated. Where alpha/beta scanning is not practicable or is unlikely to produce meaningful data (e.g., on soil surfaces), other methods such as static measurements at random locations correlated with relative ranking of concentrations may prove useful in lieu of scanning to select locations for judgmental measurement or sampling. In addition, scanning in this general sense also includes the use of conveyorized monitoring systems used to screen and segregate soil or possibly rubblized construction material.

The general category of instrumentation applied to subsurface final status decision units are subdivided based on geologic (e.g., soil and bedrock) or man-made decision units, specifically subgrade structural walls and floor slabs. Separate from these structural units are media such as embedded or underground pipes and process systems/components. The FSS for remediated soil excavation surfaces (soil or bedrock) and intact subsurface building surfaces (walls and floor slabs, and sub-slab soils) are performed in situ. However, overburden soils or structural materials removed and planned for return to an excavation as reuse/backfill material may be fully characterized, such that FSS data quality and quantity requirements are met, either in situ prior to excavation in the case of overburden soils and prior to demolition and sizing of structural materials (e.g., above-grade buildings) or surveyed for reuse ex situ. Borrow material from other site locations may similarly be characterized in situ prior to use as backfill or ex situ after being excavated and stockpiled. Detailed guidance will follow for the tabulated surface scenarios and media type that are being introduced. Table 2.1 summarizes the surface scenarios and media categories—soil, structural, and piping—and where applicable, references current NRC guidance in NUREG 1757, Vol. 2, Rev. 2 (2022). Conceptual site model guidance is also referenced because the assumed model used for DCGL development is likely to affect the methods used to demonstrate compliance with those DCGLs.

The instrumentation and methods provided in this guidance demonstrating compliance for the FSS radiological investigations of subsurface soil excavations and structural media type (including bedrock) decision units will include using detectors appropriate to the radiation emissions and to the particular use application such as scanning and quantitative field measurements, or sampling and laboratory analysis. Although technology advancements in detector carrier (i.e., autonomous vehicles or other remote sensing applications) and computer-based data management and assessments applications and algorithms are ever evolving, the scanning and measurement instrumentation and physical sampling and analysis methods remain relatively constant. Most improvements involve better detection sensitivities through enhanced electronics or computer-based data manipulations. For example, improvements include stripping of background interferences and automation of statistical assessment and presentation. The following sections describe radiological detectors for scanning and/or measurement applications, the media type application, and data uses.

Table 2.4 summarizes the common radiation detection instrumentation that may be used during a subsurface FSS. The table presents the corresponding radiation type and primary applicable media, noting that some detectors can be used, although not ideally, to survey multiple media types. For example, a hand-held plastic scintillator can be used to measure radiation levels emanating from soil, although this detector is traditionally used in structural surface surveys. Similarly, an NaI(Tl) can be used to scan for gamma radiation emanating from floors and walls of a structure, although this detector is traditionally used to locate volumetric contamination. The ROC mixture; the type, energy, and yield of emissions; action levels (e.g., DCGLs); medium type and other factors are used to select appropriate detection equipment. The licensee will be required to select instruments that optimize ROC detection (see Chapter 2 of NUREG-1507 (NRC 2020a) for additional information).

Table 2.4. Detectors Applicable to Subsurface Survey Media

Portable Surface Source Radiation Detectors		
Detector	**Radiations**	**Application**
Gas Proportional (Hand-held or floor monitor)	Can configure for alpha-only, beta-only, or alpha-plus-beta	• Qualitative radiation scanning with results in cpm; locate elevated areas. • Quantitative radiation measurement (e.g., for 1 min) with cpm results converted to dpm/100 cm^2 (Bq/cm^2) using appropriate efficiency and other conversion factor(s) to compare to surface DCGLs. • Relatively high efficiency compared to other hand-held detectors. • Large detectors (e.g., 500-600 cm^2 floor monitors) available; can be configured for more relatively fast wall and floor scans.
ZnS(Ag) (Hand-held)	Alpha	• Qualitative radiation scanning with results in cpm; locate elevated areas. • Quantitative radiation measurement (e.g., for 1 min) results converted to dpm/100 cm^2 (Bq/cm^2) to compare to surface DCGLs.
GM (Hand-held)	Beta	• Qualitative radiation scanning with results in cpm; locate elevated areas. • Quantitative radiation measurement (e.g., for 1 min) results converted to dpm/100 cm^2 (Bq/cm^2) to compare to surface DCGLs.
Dual Phoswich (Hand-held)	Dial setting for alpha-only, beta-only, and alpha-plus-beta	• Qualitative radiation scanning with results in cpm; locate elevated areas. • Quantitative radiation measurement (e.g., for 1 min) results converted to dpm/100 cm^2 (Bq/cm^2) to compare to surface DCGLs. • Trade convenience (all-in-one detector) for measurement efficiency.
Plastic Scintillator (hand-held)	Primarily beta (gamma)	• Qualitative radiation scanning with results in cpm; locate elevated areas. • Quantitative radiation measurement (e.g., for 1 min) results converted to dpm/100 cm^2 (Bq/cm^2) to compare to surface DCGLs. • Also responds to gamma radiation (can give false positive in near gamma radiation sources) and response to alpha activity contributes to observed counts.

Surface Contamination Monitor (cart-mounted, large area gas proportional or scintillator)	Can configure for alpha-only, beta-only, or alpha-plus-beta	• Computer-based data acquisition and management system for characterizing alpha and beta contamination on flat surfaces.
Portable Volumetric Source Radiation Detectors		
Detector	**Radiations**	**Application**
FIDLER: NaI(Tl) and CsI(Tl)	Low energy photons ~10 to 200 keV	• Surface scanning for low energy gamma emitters such as Am-241 and plutonium isotopes. • Results in cpm can be correlated, in some cases, to pCi/g (Bq/kg) with well characterized source and technical basis for efficiency and geometry (FOV) factors.
NaI(Tl) 1 × 1, 2 × 2, 3 × 3, and larger	Gamma ~30 to 3,000 keV	• Surface or non-planar (e.g., pipe) scanning for gamma emitting radionuclides. • Results in cpm can be correlated, in some cases, to pCi/g (Bq/kg) with well characterized source and technical basis for efficiency and geometry (FOV) factors.
CsI(Tl)	Gamma ~30 to 3,000 keV	• Surface or non-planar (e.g., pipe) scanning for gamma emitting radionuclides. • Results in cpm can be correlated, in some cases, to pCi/g (Bq/kg) with well characterized source and technical basis for efficiency and geometry (FOV) factors. • Compact detector good for down-hole measurements, scanning and direct measurements of the interior of embedded piping.
Non-planar detectors	Alpha, Beta, Gamma	• Scanning non-planar (e.g., pipe) systems inaccessible by other means. • Can configure with various cylindrical gas proportional alpha-beta detectors and cylindrical (Cs[Tl]) and spherical (NaI[Tl]) gamma detectors; results in cpm. • Can attach a camera and multi-channel analyzer (for gamma spectrum).
Plastic Scintillator (large volume, array)	Gamma	• Surface scanning for gamma emitting radionuclides. • Results in cpm can be correlated, in some cases, to pCi/g (Bq/kg).
Radio-Isotope Identification Detector (NaI, LaBr, CdZnTe)	Gamma	• Direct measurement to identify (not quantify) gamma emitting radionuclides. • Small hand-held units.

HPGe	Gamma	• Identify and quantify in situ gamma emitting radionuclides averaging over FOV; collimators can be used to limit FOV. • Results in pCi/g (Bq/kg) or pCi/m^2 (Bq/m^2) to compare directly to volumetric DCGLs. • Can be used, given technical basis, to replace volumetric samples.
Bulk Source Radiation Detectors		
Detector	**Radiations**	**Application**
Conveyorized Systems (NaI, HPGe, or plastic scintillator)	Gamma and beta	• Scan bulk material passing by detectors. • Detector arrays, supporting electronics, and an automated data acquisition subsystem. • Segregates (sorts) materials.
In Toto Systems (NaI, HPGe, or plastic scintillator)	Gamma	• Identify and quantify (pCi/g or Bq/kg) containerized gamma emitting radionuclides averaging over fixed geometry (e.g., using an HPGe). • Direct measurement to identify (not quantify) gamma emitting radionuclides (e.g., using a plastic scintillator).

2.6.3.1 Bulk Materials Survey Systems for Reuse and/or Borrow

Reuse and borrow materials can be measured in situ, prior to shipment to the excavation/substructure site, or ex situ using a variety of techniques. For example, soil from a borrow site can be surveyed in situ using conventional methods such as with a hand-held 2×2 NaI(Tl) detectors. Materials are then excavated and transported to the SSU, and ultimately deposited in an excavation or substructure. The materials can also be excavated at the borrow site, transported to a laydown area, spread over the ground surface, surveyed using conventional methods, and picked up and transported to the excavation or substructure. However, large volumes may be required to complete backfilling operations, justifying the use of automated systems designed to screen bulk material. Automated systems may also be prudent when reuse materials may contain elevated areas that will fail the MAC. Existing guidance in NUREG-1761, “Radiological Surveys for Controlling Release of Solid Materials,” provides a general overview on the use of bulk materials survey systems such as conveyorized survey monitors and portal monitors (NRC 2002). The white paper titled “Guidance on Surveys for Subsurface Radiological Contaminants” (SC&A 2022) provides additional guidance on conveyorized survey monitors specifically as it relates to the reuse of bulk materials. Given the availability of information from other published sources, this guidance is limited to a general description of these systems.

Conveyorized Survey Systems. Conveyorized survey monitors such as the examples illustrated in Figures 2.8 and 2.9 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/reusable) 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 finally to a disposal container or an intermediate pile. The most common detectors in use are NaI(Tl) crystals for gamma detection and thin-window proportional counters for beta detection. There are many variables that impact a systems MDC including, but not limited to: detector array characteristics, scan speed, contaminant thickness and density, gamma radiation energy and frequency, and beta radiation energy and frequency. These and other factors are evaluated by the licensee while selecting conveyorized survey monitors.

The detection ability of NaI(Tl) detectors is dependent on the design, quantity, and electronic configuration of selected detectors. As an example of an expected detection capability, a hypothetical system is configured with three moderately sized 3 x 3 cylindrical crystals with supporting electronics. The detectors are operated in tandem in a detector bank and the total detector volume per bank will therefore be about 1000 cm^3. An estimate of the MDC is made 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 (one-inch) thick layer of soil containing Cs-137 is expected to be about 2 pCi/g (74 Bq/kg) and will decrease to 0.7 pCi/g (26 Bq/kg) when a soil-like medium thickness is increased to 10 cm (3.9 inches). NUREG-1761 provides an example for beta detection so that gamma and beta system capabilities can be compared.

Beta particles originating within or on a target media usually undergo significant interaction before reaching the sensitive volume of a conveyorized survey monitor detector. Therefore, the process for estimating detection ability is significantly more problematic than when evaluating detection capability for gamma emitting radionuclides. The most common type of detector for this application is a thin-window gas-flow proportional detector using P-10 gas. Such detectors have a thin Mylar entrance window with a density thickness ranging from less than 1 to a few mg/cm^2. Scan MDCs are more highly variable for gas-flow proportional detector compared to NaI(Tl) systems due to multiple factors described in NUREG-1761. For example, the Cs-137 MDC for a 2,500-cm gas proportional detector (measuring beta) is expected to be on the order of 20-30 pCi/g (740-1,100 Bq/kg), or an order of magnitude higher compared to the Cs-137 MDC when detecting gamma emissions. Beta-only ROCs such as Tc-99 can have MDCs in the hundreds of pCi/g (thousands of Bq/kg), so the licensee will be required to assess the systems detection capabilities against MAC—a process that parallels the detector-selection process for designing conventional surveys.

***In Toto* Assay Systems.** *In toto* assay system such as ISGS systems, drum and box counters, tool and bag monitors, and portal monitors are used by some licensees to clear (i.e., release) materials. These same systems may be used to help determine if materials are suitable for reuse, although these systems are most likely to be used as a last-chance check measure rather than the system of process for demonstrating compliance with MAC. In either case, *in toto* systems are briefly discussed given some licensees may incorporate them into the materials scanning process.

In toto survey techniques can be used to demonstrate compliance with the average contamination level over the entire material decision unit and can be used as a technique for measuring individual samples. When used to measure contamination over the entire material decision unit, this release survey approach is well suited for solid materials that do not have a potential for small, elevated areas of radioactivity (i.e., solid materials classified as Class 2 or 3).

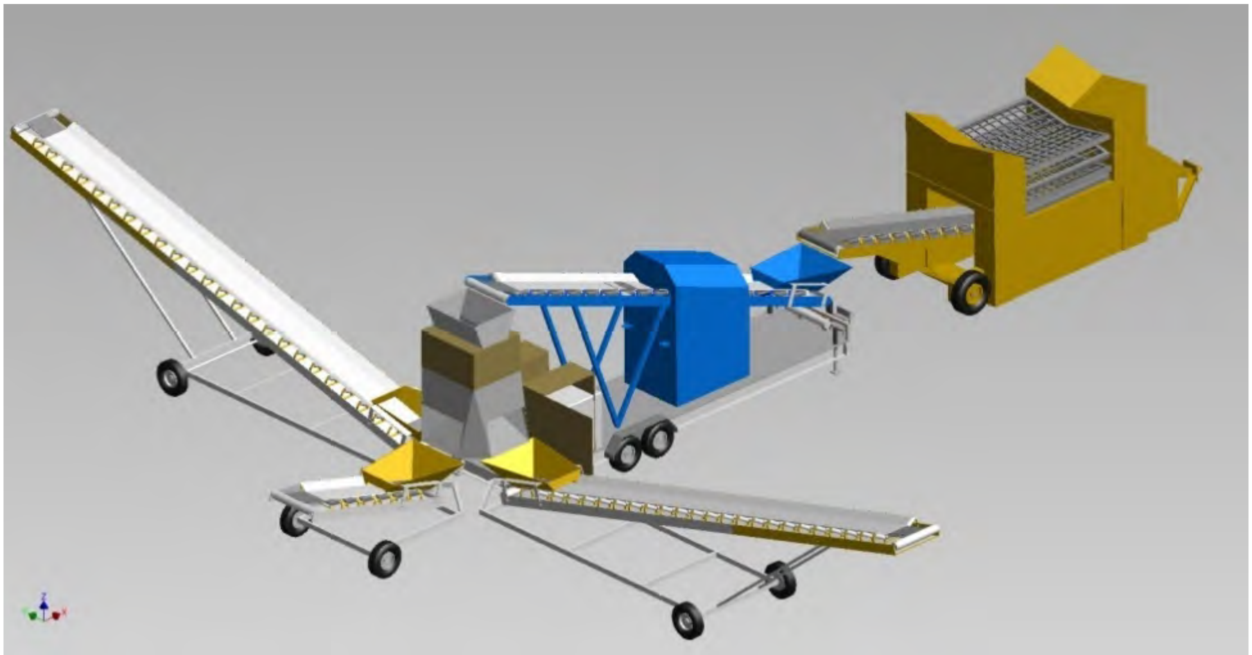


Figure 2.8 Example (ANTECH) Soil Measurement and Segregation System.
See Appendix J in SC&A (2022) for Additional Information About Various Systems.

Figure 2.9 Example (Iso-Pacific S3) Soil Sorting System.
See Appendix J in SC&A (2022) for Additional Information About Various Systems.

When small, elevated areas of radioactivity are potentially present (e.g., Class 1 materials), their impact on the average contamination level should be properly addressed during the calibration and efficiency determination for *in toto* survey techniques. Alternatively, when potential small, elevated areas of radioactivity are a concern, it may be appropriate to consider combining the *in toto* techniques with conventional scanning for locations of elevated direct radiation.

As with other survey methods, the DQO process should be used to establish the appropriate survey coverage. The material's classification should be considered when setting the size of the material survey unit. For example, the amount of material comprising Class 1 decision units may be smaller than either Class 2 or 3 decision units. Alternatively, it may be reasonable to maintain consistent survey unit sizes for all material classes, while adjusting the survey coverage based on classification. In this situation, the tool monitor might be used to assay 100 percent of the materials in Class 1, while smaller fractions of the total material would be analyzed in Class 2 and 3 survey units. Regardless of classification, the delineation of survey units may also be based on the intended reuse of the material and whether various $DCGL_V$s are used for different surface and subsurface strata (e.g., reuse of materials at the bottom of the excavation versus at the surface). Regardless of the selected approach, the solid materials having the greatest potential for contamination should receive the highest degree of survey coverage.

***In Situ Gamma Spectrometry*.** An ISGS system typically consists of a semiconductor detector, electronics for pulse amplification and pulse height analysis, a computer system for data collection and analysis, and a portable cryostat. The most common detector is the HPGe semiconductor, but other semiconductors such as developing room temperature variants can be deployed. The average contamination in the material determined by the ISGS system should be representative of the true average for comparison to an action level (e.g., an MAC). Developing an appropriate calibration factor (i.e., measurement efficiency) for the measurement geometry is non-trivial. State-of-the-art systems provide software where a user can input a specific measurement geometry and a geometry-specific efficiency is returned. Several factors should be considered when modeling a specific measurement geometry, including media density, media composition, and contamination distribution. These factors are determined prior to the FSS during characterization or other phases of the RSSI process, so that during the FSS, comparison of ISGS results to DCGLs are defensible. When contamination is distributed at depth, often it is necessary to collect core samples to develop a depth profile. The resulting depth profile can then be used to model the detector efficiency.

For materials with uniform or near-uniform contamination, only one measurement, from any orientation, may sufficiently determine the average contamination. For materials that do not have uniform contamination, different ISGS measurement approaches may be necessary to determine a more accurate average contamination level. For instance, for Class 1 materials that potentially contain small, elevated areas of radioactivity, the ISGS calibration should address the impact the small, elevated areas of radioactivity have on the efficiency of this survey technique, so that an accurate average contamination level is determined.

One approach is to perform multiple measurements at different angles around the material, such as all four sides, and then average the measurement results. Another approach, which is commonly used in drum counters, is to rotate the material during the measurement time. However, rotating a pallet of pipes or wire can be unwieldy, if not impossible, so to effectively rotate the material, one might perform part of one measurement at each location around the material. For example, suppose a count time of 40 minutes was required to meet the required detection sensitivity and the material is measured from all four sides. The first 10 minutes of the single measurement would be performed, the acquisition would then be paused while the detector was moved to the second measurement location, and then the acquisition would continue for another 10 minutes. This process would be repeated for the remaining two positions.

As with any radiation measurement instrumentation, the ISGS equipment should be managed by the licensee's QA/QC program. There are, however, special considerations for ISGS measurements. For example, it is good practice to collect QC measurements for hand-held scanning instrumentation at the beginning of the day at a minimum, and preferably at the end of the day in addition to the beginning of the day. ISGS electronics are more sensitive to changes in environmental conditions than typical scanning instruments, and QC measurements that bracket a day's activities may be insufficient to identify deviation in operating parameters during the day. Temperature and/or humidity changes may, for example, cause the signal to drift from one measurement to the next. The licensees QA/QC program could establish QC measures to ensure ubiquitous radionuclides (such as K-40, Pb-214, or Bi-214) are identifiable in the results within established tolerances. The licensee should also periodically verify that non-intrusive ISGS measurements and intrusive (e.g., core) samples are in general agreement. The QA/QC program will have to determine the threshold for "agreement," noting with caution that different measurement methods can produce different results. Because the ISGS measurement averages activity over the FOV, the licensee could collect an intrusive composite sample representing the FOV and compare results to the ISGS result. The number of increments in the composite samples should be established by the QA/QC program. ISGS versus composite results may not be similar when the contaminant is distributed heterogeneously throughout the detector FOV. The licensee should explain how to interpret differences by measurement technique (i.e., composite or ISGS), and how that influences follow-up actions and decision-making (e.g., differences in assignment of investigation levels for the two different methods). The licensee should also consider which locations are best for performing verification measurements. An ideal location may be where suspected contamination is uniformly distributed at concentrations near the DCGL. This may be preferred because decisions at background and at levels well above DCGLs are easy to justify, while decisions near the DCGL may require professional judgment or testing. In any case, the licensee's QA/QC program should be based on industry standards such as ANSI N42.28-2002 (IEEE 2004) or similar.

The licensee should establish a technical basis document that describes the performance characteristics of their ISGS. The document should discuss topics including calibration approach, sensitivity, measurement uncertainty, and QA/QC evaluations. One approach to performing QC of the measurements system is to collect samples/measurements representative of the detector FOV and compare the results to the ISGS estimated value. Unfortunately, regulatory guidance for development of a robust ISGS measurement program for decommissioning applications is limited. Licensees can, however, consult guidance such as the "Performance Demonstration Program Plan for Nondestructive Assay of Drummed Wastes for the TRU Waste Characterization Program" (DOE 2020) for an example performance demonstration program (PDP). The referenced PDP serves as a quality control check for characterization data used to demonstrate compliance with WAC for the Waste Isolation Pilot Plant. Although tailored to measurement of special nuclear material, NUREG/CR-5550, "Passive Nondestructive Assay of Nuclear Materials," provides a textbook like discussion of passive nondestructive assay methods (NRC 1991).

***Volume Counters*.** Various designs of volume counters can be used to quantify surface activity or total activity. Volume counters, while generally designed for specific counting applications, have common characteristics. These include a counting chamber, array of detectors, and electronic package for analysis. The counting chambers are designed specifically for the measurement application. The size determines what type of materials or containers the system is capable of measuring. Volumes range from small items to large shipping containers. A variety of detectors, including gas proportional, plastic and NaI(Tl) scintillators, HPGe semiconductors, and long-range alpha detection configurations, are used in volume counters, depending on the application. Many designs focus on detecting specific waste streams (e.g., transuranic waste with a high throughput). Systems designed to quantify alpha and/or beta surface activity use gas proportional and plastic scintillator detectors or long-range alpha detection. Plastic and NaI(Tl) scintillators and HPGe semiconductor detectors are used for volumetric gamma radioactivity.

***Portal Monitors*.** A common example of a portal monitor is a truck or rail car radiation detection system, as illustrated in Figure 2.10. These use large area plastic scintillation or NaI detectors to detect buried radioactive sources in bulk material. The radioactive sources are identified by detecting small changes in the ambient gamma background. Entities in the United States have used portal monitors upon receipt of materials in incoming shipments. Advances in portal monitor technology may one day allow surveyors to use this technique as a primary material survey technique. A licensed facility may use portal monitors to scan materials prior to leaving the site—those same monitors can be used to screen reuse/borrow materials prior to use a backfill.

Figure 2.10 Portal Monitor at Federal Port of Entry.

2.7 <u>Sampling Subsurface Media</u>

The following discussion presents guidance on sample location planning, the depth of sampling, and other considerations such as possible data collection methods by medium type.

2.7.1. Sample Location Planning

Random samples are necessary for performing statistical tests and for estimating population parameter such as the mean, median, and standard deviation. For example, cleanup goals are often based on average concentrations—random sampling provides the best estimate of average concentrations because judgmental samples can introduce bias. MARSSIM specifically describes methods for testing whether the site concentrations are statistically above the $DCGL_W$ by using only results from randomly selected sample locations. Recall also from MARSSIM that sample locations for Class 1, Class 2, and Class 3 areas are randomly selected, the difference being that Class 1 and 2 locations include a systematic grid with a random start location, while Class 3 guidance includes an ordinary random distribution (no grid). Therefore, when sample data from an SSU will be used for either inferential statistics (e.g., a statistical test) or descriptive statistics (e.g., mean and variance), the licensee will randomly select sample locations. MARSSIM Chapter 4 discusses how to set up a reference system when identifying sample locations by hand, or FSS planners can use software such as VSP to randomly select sample location and grid spacing, as appropriate. Whichever approach the licensee takes identifying the random sample locations, random sampling can be used in SSUs, at onsite reuse sites, or off-site borrow sites.

The DQO process is used to develop acceptable sampling density, which may include probabilistic, judgmental, or a combination of both. Furthermore, other techniques may be used to supplement the basic sampling design. These techniques include the addition of supplementary methods such as composite, adaptive cluster, and ranked set sampling. For example, composite sampling (with increment reanalysis) may be used to reduce analytical costs for cases where a large number of statistical samples are required. Additional information on these methods is provided in the “Guidance on Choosing a Sampling Design for Environmental Data Collection for Use in Developing a Quality Assurance Project Plan” (EPA 2002b). Table 2.5 presents sample distribution strategies depending on the project objectives, site-specific conditions, and other factors. The expectation is that ordinary random or systematic designs are suitable for most sites and SSUs.

Judgmental samples are sometimes necessary as a primary means of investigating anomalies, filling data gaps, or otherwise collecting data to address a specific project need. The location of judgmental samples may be selected as part of the FSS planning process (e.g., process piping), or can be selected as the field effort progresses (e.g., at an elevated area). In either case, random tools, such as those described in MARSSIM or as implemented with VSP, are not required to locate judgmental samples.

Probabilistic sampling of materials planned for stockpiling and reuse are more readily accomplished prior to excavation of overburden, reuse, or borrow soil and prior to rubblizing structural materials. Sampling of soils undergoing segregation via conveyorized monitoring are sampled randomly or systematically from the discharge. Systematic or random sampling may be based on time or volume intervals developed during the DQO process. Soil or rubble stockpiled prior to any sampling will also be sampled either randomly or systematically (based on classification) as a three-dimensional versus planar population where a z-coordinate is also required. The scanning of these materials, if from Class 1 or 2 areas, will need to be accomplished either prior to excavation/demolition, completed by the monitoring system as they were being processed, or in lifts while being placed in the final end state position.

Table 2.5 Sample Distribution Strategies

Design	Sampling Goal	Advantages/Disadvantage
Judgmental	Gather data from specific location	Advantages: • Simple to implement; based on professional judgment. • Can be used to fill data gaps, investigate elevated areas or areas with high risk for contamination. Disadvantages: • Data should not be used to estimate the mean, variability, confidence levels, and other statistical parameters in a decision—introduces bias.
Ordinary Random	Hypothesis testing and estimating population parameters such as mean and variability	Advantages: • Commonly used to estimate the mean, variability, confidence levels, and other statistical parameters in a decision unit. Disadvantages: • Random selection process can lead to location clustering. • Assumes concentrations are relatively homogeneous, so is less suitable when concentrations are heterogeneous—less effective for locating elevated areas. • Can be challenging to implement when each location should be identified in the decision unit.
Quasi-Random	Hypothesis testing and estimating population parameters such as mean and variability	Advantages: • Can be used to estimate the mean, variability, confidence levels, and other statistical parameters in a decision unit. • Minimizes clustering by accounting for the distance between random locations. Disadvantages: • Same disadvantages as ordinary random. • Licensee may choose systematic grid over quasi-random when it is important to locate elevated areas.
Systematic Grid	Hypothesis testing and estimating population parameters such as mean and variability	Advantages: • Still random (use random start), so retain the advantage of ordinary radon while also limiting the size of unidentified elevated areas. • Can be easier to implement in the field than random—find one grid node location then lay down grid versus independently locating each random location.

		Disadvantages: • Can confuse field personnel when grids encompass both walls and floors. • When using software such as VSP, the number of grid nodes may not match required number of samples (N) in irregularly shaped decision unit.
Adaptive Cluster (Gilbert 1987)	Delineate contamination boundaries when pockets of contamination are sparsely distributed	Advantages: • Randomly sample *N* nodes from equally spaced/sized grid, so retain the advantages of ordinary sampling approach. • Sample adjacent nodes when an investigation level is exceeded, so elevated areas can be bounded. • Useful when ROCs are HTDs. Disadvantages: • Samples from adjacent areas are not used in hypothesis testing or estimating the mean, variance, etc. for the decision unit as a whole. • Random selection process can lead to primary location clustering. • Can be challenging to implement when each primary location should be identified in the decision unit.
Composite (Gilbert 1987, Jozani and Johnson 2011, Vitkus 2012)	Estimate of the mean	Advantages: • Lowers cost by collecting fewer samples. • Can be used with random or systematic design, although easier to plan when using systematic gridding. • Can couple with other methods to investigate only individual elevated areas when scanning is ineffective or impossible (e.g., collect a composite sample in an ordinary random location that cannot be scanned). Disadvantages: • Need an investigation level to trigger analysis of composite increments (licensee should decide how many increments and how to calculate investigation level). • Loses information about contaminant variability.
Rank Set Sampling (Jozani and Johnson 2011)	Estimate of the mean	Advantages:

		• Lowers cost by collecting fewer samples by combining field screening tools with samples. Disadvantages: • Ineffective when local sources of shine or geometric effects (e.g., sidewalls) impact ambient radiation levels. • Lose information about contaminant variability. • Less intuitive than other sample designs. • Requires radiation detector that can detect contamination below the DCGL, relying on a correlation between detector response and material concentration.

2.7.2. Depth of Sampling

Soils and Structures. Because source geometry assumptions (e.g., distribution, thickness, depth, and area of residual radioactivity) are directly related to dose (or risk), the FSS should, to the extent practical, be designed consistent with these source geometry assumptions. For example, if vertical heterogeneity is an issue and DCGLs are sensitive to the distribution of residual radioactivity within the soil column, DCGLs could be developed for different soil intervals (e.g., 0 to 5 cm and 5 to 15 cm). Depth discrete sampling may then be necessary for comparison against the DCGLs developed for each soil interval. For certain radionuclides and pathways (e.g., Cs-137 and external dose pathway), depth discrete sampling may also be important to ensure that higher concentration residual radioactivity located near the surface is not diluted with clean or cleaner radioactivity located deeper in the soil column, which could lead to an underestimate of risk. Likewise, the thickness of residual radioactivity can also be important to risk. If residual radioactivity is located deeper in the soil column, than assumed in the dose modeling, then the risk could be underestimated. Subsurface residual radioactivity should be adequately characterized and if present, appropriate methods should be developed to evaluate whether residual concentrations satisfy requirements (the MARSSIM methodology summarized in Appendix A was developed for surficial soil and building surfaces only; other methods may be necessary to make decisions regarding release for sites with subsurface or volumetric residual radioactivity).

Three main ideas are as follows:

1. Characterization data should provide information that describes the depth of contamination.
2. The applicable regulatory guidance may influence the sample depth.
3. The dose model assumes a depth of contamination.

The licensee will be required to balance these three factors when establishing a sample depth, and the appropriate time to do so is during DQO development.

Reuse and Borrow Materials. Various aspects of sampling, such as depth, depend on whether sampling is performed while the material is still *in situ* or after excavation. Regardless, the sampling should be representative of the total material, accounting for any vertically- or horizontally related spatial differences in the material. Many of the same guidelines for soils within an SSU also apply to reuse and borrow materials. It is good practice, for example, to use the same equipment, procedure, and laboratory analytical methods for the reuse/borrow soil as those used within the SSU—data from the reuse/borrow site should be of the same type and quality as those from the SSU.

Miscellaneous Materials. For miscellaneous materials such as embedded piping, transfer canals, etc. the depth of the sample will be determined on a case-by-case basis. It may be, for example, that the licensee will only be able to collect limited material/residue that is both physical present and safely accessible. The challenge of accessibility should be balance against the risk of leaving materials uncharacterized. Does the material represent a threat to NTE or EMC thresholds, a potential groundwater contamination concern, or contribute a significant fraction of the release criteria? These are questions the licensee should address when considering how aggressively to pursue the characterization of miscellaneous materials.

2.7.3. Sample Collection Considerations Applicable to Subsurface Decision Units

A crucial consideration when developing DQO Steps 3 through 7 for subsurface decision units is ensuring that the sampling method selected, and the data output, assessment, and reporting are directly comparable to the DCGL units prepared for the CSM. Otherwise, if methods planned result in data that with different units, a defensible and verifiable technical basis document is required to support assumptions on how the measurement results are either converted or otherwise directly used to demonstrate compliance with the DCGLs. Consider the following example to illustrate this point.

> A structural decision unit (e.g., basement walls and floor slab) will remain in place. Characterization has shown that the construction material is volumetrically contaminated with a mixture of activation products. The $DCGL_V$ modeling output is in terms of pCi/g (or Bq/g) average activity within the volume of the structure, from which an operational or effective DCGL can be calculated based on area, thickness, and density characteristics of the construction material. Multiple methods for demonstrating compliance with DCGLs are considered:
>
> 1. The most direct method is to collect volumetric samples during the FSS where each sample represents a fraction of the total volume of material. Samples are collected and analyzed for all ROCs, and the results reported in the same units as the DCGL.
> 2. Another relatively direct approach is to collect in situ gamma spectrometry measurement instead of physical samples, with the system calibrated to report results in pCi/g (or Bq/g). Non-gamma emitting ROCs are accounted for using a surrogate radionuclide approach that requires a technical basis for the results and assumptions used to calculate the modified DCGL(s).
> 3. Another possible method involves only gross surface activity measurements, presuming the licensee demonstrates the assumptions of the distribution of contamination throughout the volume, what proportion of the activity is detectable by surface activity measurements, and the thickness of the detectable activity. Additional justification would include proof-of-concept data—such as correlated surface activity data and volumetric data—demonstrating at a given confidence level that when the measured surface activity is less than the calculated action level, the volumetric DCGL is satisfied.

The types of subsurface investigations, the investigation design, planning and sequencing, procedures, survey equipment and analytical equipment used, and implementing method are likely to closely mirror the MARSSIM methods commonly used for surface soil and structures. Expanded discussions are provided for unique subsurface scenarios for which there is currently limited guidance. Table 2.6 presents a range of FSS activities for various subsurface media with general notes and issues associated with each activity. Some media require distinct study questions and hence analytical approaches and may represent independent survey units based on surface type, action level, or other parameters—these are addressed on a case-by-case basis.

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
Soil Excavation—Floor and Wall		
Gamma radiation scanning	Assess general gamma radiation levels across the surface layer (generally top 15-30 cm) to support classification decisions and identify anomalies for further investigation	Notes: • Primary FSS activity (with statistical/representative sampling). • MARSSIM guidance for classification is appropriate, as are scan density coverages based on classification. • Select instrumentation and methods to optimize detection potential and to meet scan MDC requirements. Issues: • Limited utility unless ROCs are gamma emitters, or when gamma emitters are not co-located with non-gamma emitters. • When the coverage goal is infeasible, the licensee should justify alternative methods to address radiological conditions of unscanned areas (e.g., composite samples). • When some surfaces are only accessible remotely by using cranes, manlifts, etc., the licensee should match equipment configuration to the extent practical (e.g., cable lengths) to help ensure consistent response. • “Shine” sources (gamma radiation for adjacent materials) can interfere with detection sensitivity; edge or well effects may occur on non-planar surfaces.
Supplemental alpha/beta measurements	Provides supplemental and/or collaborative data to provide information for some HTD ROCs, assist with judgmental sampling decisions	Notes: • Provides additional qualitative data for non-gamma emitting ROCs or when gamma emitters are not always co-located with non-gamma emitters. Issues: • Unlikely to have optimized, reproducible measurement conditions (soil surfaces likely to be non-uniform). • Alpha radiation unlikely to penetrate through dust/moisture layer to detector (limited utility); beta measurements limited to thin surface layer.

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
		• No specific regulatory guidance on techniques to generate quantitative data (i.e., directly comparable to volumetric DCGLs). • Requires technical investigation and evaluation to develop procedures and supporting documentation.
Statistical/representative sampling	Random samples used in statistical assessments including decision problems (hypothesis tests), estimation problems (e.g., mean, median, standard deviation estimates), inventory estimation, presence/absence determination, and other representative assessments.	Notes: • Primary FSS activity (with scanning). • Primary tool for assessing compliance with $DCGL_W$, $DCGL_V$, etc. • MARSSIM guidance for required number and distribution of samples is appropriate where objective is to demonstrate compliance with dose-based limits (e.g., $DCGL_W$ values). • Insufficient for assessing NTEs criteria or identifying elevated areas (e.g., $DCGL_{EMC}$). • Sample depth increment determinations necessary to match CSM and DCGLs. Issues: • When elevated area detection is important, additional samples may replace scanning data where scanning is insufficient or infeasible; plans should clearly state the intent and procedures for supplementing or replacing scanning coverage. • Separate floor and sidewall sampling plans may be required depending on soil profile, DCGL applicability, the degree of sloping or terracing results in soil well outside the footprint of the excavation, different classification, or other factors.
Judgmental/non-representative sampling	Evaluate scan anomalies and areas with high potential for contamination, confirm classification decision, confirm concentration ratios	Notes: • Data used to assess NTEs and EMC, as appropriate. • Collect at statistical sample locations when down-hole radiation levels increase more than expected. Issues:

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
		• Judgmental sampling for EMC may be less important for SSUs (compared to SUs) depending on importance of elevated areas and conceptual modeling. • The same sample protocols used for statistical samples are used for judgmental sampling, although additional material/intervals may be collected to bound contamination.
In situ gamma spectrometry	May replace all or a portion of random or judgmental soil sampling; some licensees use to satisfy gamma radiation scanning coverage requirements	Notes: • Requires calibrations representative of required depth intervals and multiple other factors to ensure data represents DCGL conditions and contamination profile (e.g., as determined during site characterization). • May serve as an alternative under appropriate circumstances to satisfy scan requirements within inaccessible areas. • Data comparison of agreement between in situ and laboratory measurement via duplicate error ratio should be required. Would need to ensure that the laboratory samples represent FOV. Issues: • Not useful without gamma emitting ROCs. • Misleading results if actual contamination distributions do not match the source modeling (e.g., contamination is covered by relative clean layer). • Can “average out” elevated areas over the detector FOV which may not satisfy EMC evaluation requirements. • Overlapping measurements required to achieve 100% coverage when used in lieu of traditional (i.e., hand-held) scanning methods.
Bedrock Excavation Floor		
Gamma radiation scanning	Same purpose as for soil	Notes: • Soil notes apply here. Issues: • Soil issues apply here.

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
		• Bedrock likely denser than soil and ROC distribution in elevated areas may be irregular (e.g., along fissures, line sources)—evaluate potential differences when calculating scan MDCs. • Soil and bedrock may have different DCGLs and scan MDCs, thus different investigation, and action levels.
Alpha/beta measurements and investigations	Same purpose as for soil	Notes: • Soil notes apply here. • May be used to identify residues on the surface of cracks/fissures. • Where limited contaminant penetration has occurred, volumetric criteria may be converted to surface activity values based on depth to surface distribution assumptions. Issues: • Soil issues apply here. • Requires depth sampling and analysis investigations to convert volumetric DCGLs to equivalent surface activity values.
Statistical/representative sampling	Same purpose as for soil	Notes: • Soil notes apply here. • Cores may be used to assess/confirm ROC depth profile. • Where little contaminant penetration has occurred, volumetric DCGLs may be converted to surface activity levels and replaced with alpha/beta measurements (i.e., assess as if the bedrock is a concrete floor). Issues: • Soil issues apply here. • Sufficient sample volume may be difficult to collect without mechanical assistance (core sampler, hammer drill, etc.).
Judgmental/non-representative sampling	Same purpose as for soil	Notes: • Soil notes apply here. • Likely target medium is residue (e.g., soil) in cracks and fissures.

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
		Issues: • Soil issues apply here. • Sufficient sample volume may be difficult to collect without mechanical assistance (core sampler, hammer drill, etc.).
In situ gamma spectroscopy	Same purpose as for soils	Notes: • Soil notes apply here. Issues: • Soil issues apply here. • Depth profile may be different than for soil requiring calibration to ensure data represent DCGL/CSM conditions.
Subsurface Structure Walls, Floor, and Slabs		
Gamma, alpha, and/or beta radiation scanning (traditional methods)	Qualitative assessment of radiation levels across the structural surface to support classification decisions and identify anomalies for further investigation	Notes: • Soil notes for gamma radiation apply here. • Alpha/beta scans are traditionally used to evaluate against surface DCGLs (e.g., in units of dpm/100 cm^2), although gamma scans may be more applicable for subsurface structures and volumetric DCGLs. • Alpha/beta scans still useful when ROCs are primarily alpha/beta emitters (e.g., Sr/Y-90). • Large area detectors can improve scan efficiency. • Gamma shine sources will not interfere (as much) with some alpha/beta detectors (e.g., gas proportional). Issues: • Soil issues apply here.
Direct alpha and/or beta surface activity measurement	Qualitative assessment of alpha and/or beta radiation levels at discrete (e.g., statistical or judgmental sample) locations	Notes: • For subsurface structures, direct alpha/beta measurements can supplement volumetric samples; volumetric results likely to be used for decision-making process. • Data can help quantify/confirm ROC concentration ratios. • Can be useful when ROCs are primarily alpha/beta emitters (e.g., Sr/Y-90).

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
		Issues: • Removable fraction measurement (smear data) usefulness limited; may be used to quantify/confirm ROC ratios.
Statistical/representative sampling	Random samples used in statistical assessments including decision problems (hypothesis tests), estimation problems (e.g., mean, median, standard deviation estimates), inventory estimation, presence/absence determination, other representative assessments	Notes: • Same notes as for soil. • Traditionally surface measurements compared to DCGLs in units like dpm/100 cm^2, although volumetric samples may be more applicable for substructure DCGLs in units like pCi/g (or Bq/g). • Contamination profile (e.g., due to neutron activation) may require incremental analysis. Issues: • When elevated area detection is important, additional samples may replace scanning data where scanning is insufficient or infeasible; plans should clearly state the intent and procedures for supplementing or replacing scanning coverage. • Statistical sample unlikely to fall on sources like embedded process piping, transfer tunnels, etc. • Separate floor and wall sampling plans may be required depending on SSU boundary definitions or other factors.
Judgmental/non-representative sampling	Evaluate scan anomalies and areas with high potential for contamination, confirm classification decision, confirm concentration ratios	Notes: • Same notes as for soil. • Traditionally surface measurements compared to DCGLs in units like dpm/100 cm^2, although volumetric samples likely more applicable for substructure DCGLs in units like pCi/g (or Bq/g). • Contamination profile (e.g., due to neutron activation) may require incremental analysis. Issues: • Same issues as for soil.

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
		• Embedded piping and other sources may require specialized equipment for sampling, and the quantity of materials may be limited (e.g., scrape residues).
In situ gamma spectrometry	May replace all or portion of random or judgmental soil sampling; some licensees use to satisfy gamma radiation scanning coverage requirements	Notes: • Same notes as for soil. Issues: • Same issues as for soil.
Subfloor Soils		
Gamma, alpha, and/or beta radiation scanning and measurement	Qualitative assessment of radiation levels across the structural surface to identify potential migration pathways	Notes: • Soil notes for gamma radiation apply here. • Alpha/beta scans are traditionally used to evaluate against surface DCGLs (e.g., in unit dpm/100 cm^2), although gamma scans may be more applicable for subsurface structures and volumetric DCGLs. • Alpha/beta scans of extracted cores can still be useful when ROCs are primarily alpha/beta emitters (e.g., Sr/Y-90), although results will be qualitative and surface efficiencies will be low. • Large area detectors can improve scan efficiency. • Gamma shine sources will not interfere (as much) with some alpha/beta detectors (e.g., gas proportional). Issues: • Soil issues apply here.
Floor coring	Quantify subfloor contamination levels, define contamination boundary, support fate and transport models, support dose modeling	Notes: • Coring locations considering multiple factors typically based on professional judgment including but not limited to the following: characterization data, source/SSU size, ROC physical/chemical forms, water table location (relative to floor base), groundwater flow direction, known or suspected migration pathways, etc. • Prudent to scan cores when extracted and/or borehole, if possible, to locate lenses of elevated activity. Issues:

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
		• Groundwater infiltration can present challenges. • Coring equipment may be limited (large equipment may be required in small, access-limited, or confined spaces). • Boreholes scan data only represent immediately adjacent soils/rock (15 to 30-cm radius). • Boreholes represent low-resistance pathway for radon infiltration.
Soils Targeted for Reuse (On-site) or Borrow (Off-site)		
Gamma radiation scanning (in situ)	Assess general gamma radiation levels across the surface layer (generally top 15-30 cm) to assess suitability for reuse	Notes: • Reasonable to use MARSSIM guidance for classification and coverage guidelines. • If categorized as unimpacted, determine scan coverage during DQO development. • Can repeat surveys with each lift, as applicable. • Select instrumentation and methods to optimize detection potential and to meet required scan MDC requirements; good practice to use same instruments and methods specified under the soil section. • Scans may identify radiological anomalies not associated with site operations. • Non-intrusive, semi-quantitative method, prior to sampling, to compare reuse/borrow radiation levels with estimated SSU background levels (for suitability). Issues: • Limited utility unless ROCs are gamma emitters. Radiation levels may change with depth (e.g., Cs-137 from above-ground nuclear testing/Chernobyl only expected in surface soils).
Beta and/or gamma radiation scanning (ex situ)	Assess general beta/gamma radiation levels of material to assess suitability for reuse	Notes: • Can be used in conjunction with, can supplement, or can replace in situ scanning at the extraction site. • Soils can be distributed across laydown area for gamma scanning; use DQOs to determine frequency of scans (i.e.,

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
		each batch/load, specified percentage, etc.) and percent coverage of laydown material (e.g., 100%, 50%, etc.). • Select instrumentation and methods to optimize detection potential and to meet scan MDC requirements. • For traditional scanning methods, good practice is to use same instruments and methods as with SSU soil. • Conveyor systems may be used to screen for gamma and beta emitting radionuclides; use DQOs to develop decision levels. <u>Issues</u>: • Limited utility unless ROCs are beta/gamma emitters. • Radiation levels may change with depth from extraction site (e.g., Cs-137 from above-ground nuclear testing/Chernobyl only expected in surface soil). • For conveyor systems, material depth and belt speed should be set to limit false negatives (i.e., miss contamination)—same concept as observation interval, scan speed, etc., with traditional survey methods.
Statistical/representative sampling	Random samples use in statistical assessments including decision problems (hypothesis tests), estimation problems (e.g., mean, median, standard deviation estimates) other representative assessments	<u>Notes</u>: • Reasonable to use MARSSIM guidance to assign class, estimate sample number, distribution method, etc.; MARSSIM method also reasonable when selecting decision problem to assess compliance. • Estimation problem may also be used at reuse/borrow site, if only needing mean, standard deviation, and other statistics. • In either case (decision or estimation), use DQOs to ensure the right type, quality, and quantity of data are collected. • Sample from area on scale/size like SSU or dose model. • Use same sampling methods, equipment, and laboratory analytical methods as those used in soil SSU. <u>Issues</u>:

Table 2.6 Data Collection Activities for Various Subsurface Media

Activity	Purpose	Notes/Issues
		• Unimpacted area that represents onsite background conditions may be difficult to identify and/or precure—compromise may be necessary. • In situ sampling at extraction site may need to be repeated (with scans) prior to each lift, for a percentage of the lifts, or a percentage of the lift area, at some specified frequency, or as otherwise determined via the DQO process. • *Ex situ* sampling in laydown areas may need to be repeated (with scans) for each lift, for a percentage of the lifts, at some specified frequency, or as otherwise determined via the DQO process.
Judgmental/non-representative sampling	Evaluate scan anomalies and areas with high potential for contamination, confirm suitability	Notes: • May not be needed except to determine if contamination is cause of scan anomalies. Issues: • Plan needs to address the level of contamination that triggers action (e.g., reject materials for reuse or borrow)—some level of contamination or elevated activity may be acceptable, depending on site-specific requirements.
In situ gamma spectrometry	May replace all or portion of random or judgmental soil sampling	Notes: • Soil notes apply here. • If in situ gamma spectrometry is used for the SSU FSS, a similar approach may be used to assess reuse or borrow material. Issues: • Soil issues apply here.

2.8 Consolidated Process Guidance by Medium

The following examples are presented to illustrate how a licensee may use the framework provided in this document to plan a FSS for subsurface materials. These examples are high-level and generic, and licensees are expected to develop more expansive planning documents that provide specific details addressing site-specific decommissioning scenarios. These examples focus on DQO development, given that DQOs are the backbone of the FSS design. For these examples, it is assumed that a range of DCGLs have been developed for the site including the following:

- $DCGL_W$ and $DCGL_{EMC}$ values for surface soil SU DCGLs,
- $DCGL_V$ values for average subsurface SSU DCGL,
- $DCGL_{V\_R}$ values for reuse/borrow material DCGLs (or MAC), and
- $DCGL_{V\_GW}$ values for migration to groundwater DCGL.

Some of the above DCGLs may apply to a given SSU or subsurface decommissioning project. It is expected that FSS projects will follow MARSSIM to the extent possible, and large soil excavation and large basement structures will follow parallel paths. The example DQOs are presented for both a soil SSU (Case 1) and a basement structure SSU (Case 2). The third example (Case 3) is for a reuse/borrow site when backfill materials will be extracted. It is possible that projects will combine aspects of these examples (e.g., for an excavation or basement that will be backfilled with reuse materials). Each case example is broken into the steps described in Figure 2.3.

2.8.1. Case 1—Example Subsurface Soils DQOs

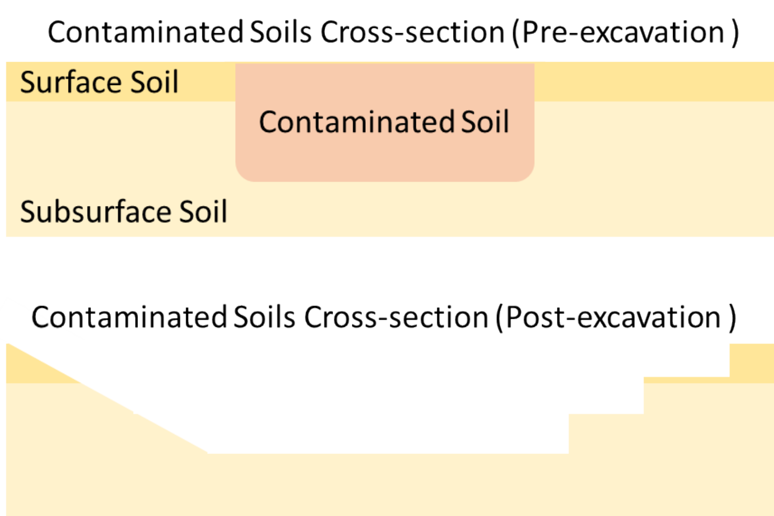


Figure 2.11 Example SSUs with Soil Floor and Walls

Case 1 Step 1. State the Problem—Define the Problem that Necessitates the Study
A large volume of soil contains residaul radioactivity levels above $DCGL_W$ values for multiple ROCs. The site will be remediated as illustrated in Figure 2.11, although it is possible that some residual radioactivity will remain across the face of the excavation. In some areas the remediation will reach bedrock. The excavation will ultimately be backfilled with off-site borrow materials, so remaining contamination, if any, will reside below clean fill. Although the licensee recognizes that this excavation does not represent a classic MARSSIM scenario, project

planners decide to implement the MARSSIM method to the extent practical. The licensee should ultimately demonstrate residual concentrations will not result in a unacceptable dose to future site inhabitants who could, at some future date, remove the backfill or excavate and redistribute contamination across the ground surface. For this site, contamination is not considered a threat to groundwater.

Case 1 Step 2. State the Study Goal—State How Data Will Be Used to Meet Objectives
The principle study question is, “Does the FSS demonstrate that residual ROC concentrations in excavation can produce a dose above the 0.25 mSv/yr (25 mrem/yr) dose limit?”

- If the answer is Yes: Alternative Action 1 is to conclude that the site does not satisfy release criteria and additional actions are required up to and including additional remediation and repeating FSS activiites.
- If the answer is No: Alternative Action 2 is to conclude that the site satifies criteria and may be backfilled and released for the intended land use.

The decision statement is: FSS (does or does not) demonstrate that residual ROC concentrations in the excavation can produce a dose above the 0.25 mSv/yr (25 mrem/yr) dose limit, and therefore additional actions (are or are not) required prior to releasing the site.

Case 1 Step 3. Identfy Decision Inputs—Identify Data and Information Needs
Inputs include the LTP/FSS; characerization data; survey and equipment management procedures; sampling and sample management procedures; the analytical statement of work; the $DCGL_W$ and $DCGL_{EMC}$ values for each ROC, and ultimately the FSS sample analytical results.

Case 1 Step 4. Define Study Boundaries—Identify Special, Temporal, and Practical Boundaries
Study boundaries include the excavation footprint and sidewalls, the sample depth (to match the conceptual and dose models), classification boundaries, and SSU boundaries. This is a large excavation with multiple SSUs, all of which are Class 1. Bedrock, if encountered represents a practical boundary (requiring different sampling equipment); however, the licensee intends to use surface soil DCGLs regardless of whether encountering soil or bedrock. Finally, the project schedule outlines temporal boundaries.

Case 1 Step 5. Develop A Decision Rule—Specify Parameters for Making Decisions
The licensee is required to assess whether average residual ROC concentrations (μ_S) in the excavation exceed average reference area concentrations (μ_R) by an amount sufficient to produce an unacceptable dose at the surface, presuming materials can become uncovered or are excavated and redistributed across the surface. In addition, the licensee should determine whether elevated areas in the excavation could reasonably result in a volume of material that exceeds $DCGL_{EMC}$ values.

The project decision rule is: *If* the FSS demonstrates that residual average and elevated area ROC concentrations in the excavation can produce a dose above the 0.25 mSv/y (25 mrem/yr) dose limit, *then* addition actions, up to and including excavation and additional FSS activities, will be conducted, *else* the decision is that the excavation concentrations satisfies criteria and the property may be released for the intended future land use.

Case 1 Step 6. Specify Performance Or Acceptance Criteria—Specific Limits on Decision Errors (Decision Problem) or Develop Performance Criteria (Estimation Problem)

A statistical test will be used to determine whether net residual radioactivity concentrations in any SSU exceed $DCGL_W$ values. The licensee selects Scenario A where the $DCGL_W$ is used as the substantial difference. ROCs are present in background, so the WRS test is selected. For this project:

H_0 = residual radioactivity concentrations in the survey unit above background are greater than the DCGLs; $\mu_S > \mu_R + DCGL_W$
H_A = residual radioactivity concentrations in the survey unit above background are less than the DCGLs; $\mu_S \leq \mu_R + DCGL_W$
Type I error (α) = 0.05 (95 percent confidence)
Type II error (β) = 0.10 (90 percent power)

Because there are multiple ROCs and associated DCGLs, the $DCGL_W$ used to estimate the number of samples is normalized (i.e., set to 1). Based on characterization data, the weighted expected mean concention is 0.3, and the weighted expected standard deviation is 0.4. The relative shift is conservatively rounded down to 1.7, and Table 5.3 in MARSSIM shows that 12 samples are required in each SSU and in the reference area (including the 20 percent increase for unusable sample results or missing samples).

Case 1 Step 7. Optimize The Design—Develop the Sampling and Analysis Plan
The VSP code is used to distribute 12 samples per SSU across the excavation using a systematic grid with a random starting point. At each sample location, a static gamma measurement is collected above the location (for information that may be used to correlate data) and in the borehole after the sample is collected (to determine if contamination increases with depth). Individual sample depth and volume has been established to match the conceptual/dose model (for depth), and the dose modeling assumptions regarding depth are based on data on the actual distribution of residual radioactivity from characterization, and analytical laboratory requirements (for mass/volume). Samples will be collected using standard hand tools for soil, although sampling of bedrock may require mechanical equiment.

All (100 percent) of the accessible areas will the scanned using NaI detectors, which have been demonstrated to satisfy scan MDC requirements. Surveyors are instructed to listen to the audible count rate and flag locations that exceed the project-specific investigation level. Surveyors will be using GPS equipment to conduct scans, so the GIS technician may also post-process data and flag any areas above the investigation level, if missed by the surveyor. The licensee will use professional judgment to determine which, if any, of the flagged locations will be sampled.

Sidewalls that cannot be safely traversed by surveyors will be scanned with mechanical assistance (e.g., and boom lift) or will be subject to supplemental judgmental or composite sampling across any unscanned areas. Composite samples may be collected in large areas (on the scale of A/N, where A is the total SSU area) inaccessible to surveyors—professional judgment will be required when inaccessible areas are smaller than A/N. Note that composites do not replace statistical samples, although additional material from the primary location may be composited with additional locations in the inaccesible areas.

2.8.2. Case 2—Example Basement Substructure DQOs

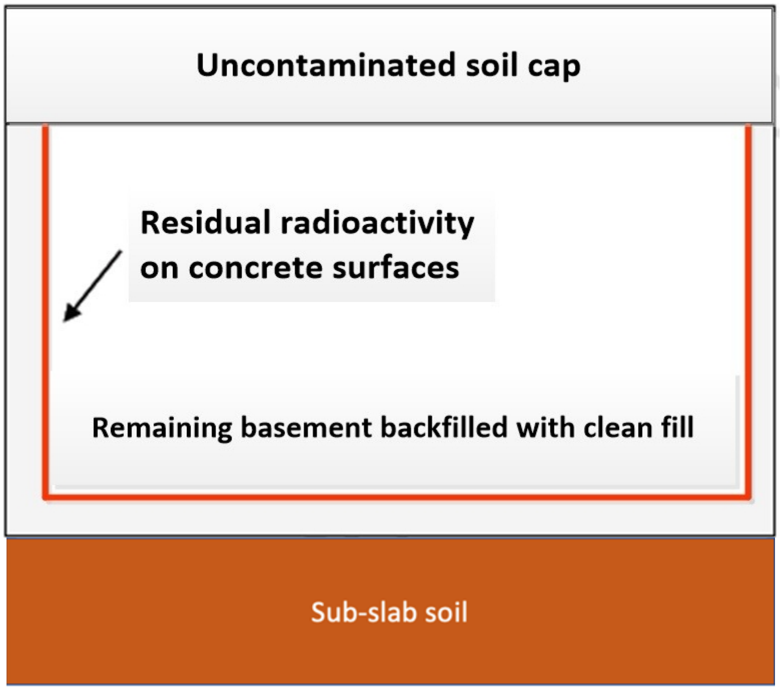


Figure 2.12 Example Structural (Basement) SSUs.
Image Credit: Modified from Figure J.2 (NRC 2022).

Case 2 Step 1. State the Problem—Define the Problem that Necessitates the Study
A large basement structure illustrated in Figure 2.12 contains contamination levels above DCGLs for multiple ROCs. The site will be remediated although it is possible that some residual radioactivity will remain throughout the structure. It is also possible that contamination has leached through the basement floor to underlying soils, presenting a threat to groundwater. Multiple contaminated floor/wall penetrations are present, some of which will remain in place. This project presents a problem generally inconsistent with MARSSIM FSS methods, although the licensee plans to utilize applicable MARSSIM guidance for the FSS. The licensee should demonstrate residual concentrations will not result in an unacceptable dose to future site inhabitants who could, at some future date, excavate and distribute portions of the contaminated basement structure across the ground surface. The licensee should also ensure that residual contamination levels that remain as a whole could not result in the threat to groundwater and future groundwater-dependent doses.

Case 2 Step 2. State the Study Goal—State How Data Will Be Used to Meet Objectives
The licensee should address the potential for leaving structural materials that could 1) be excavated thus distributing contaminated material over the surface, and 2) lead to leaching of residual radioactivity to groundwater. The licensee develops two principle study questions to address both problems.

Principle study question 1 is, “Does the FSS demonstrate that residual ROC concentrations in and below the basement structure could produce a dose above the 0.25 mSv/y (25 mrem/yr) dose limit, assuming contaminated materials will be excavated and distributed across the surface?”

If the answer is Yes: Alternative Action 1 is to conclude that the site does not satisfy release criteria and additional actions are required up to and including additional remediation and repeating FSS activiites.

If the answer is No: Alternative Action 2 is to conclude that the site satisfies criteria and may be backfilled and released for the intended land use.

The decision statement 1 is: FSS (does or does not) demonstrate that residual ROC concentrations in and below the basement structure can be uncovered or excavated and produce a dose above the 0.25 mSv/y (25 mrem/yr) dose limit after being distributed at the surface, and therefore additional action (are or are not) required prior to releasing the site.

Principle study question 2 is, "Does the FSS demonstrate that residual ROC concentrations in and below the basement structure can produce a dose above the 0.25 mSv/y (25 mrem/yr) dose limit, assuming residual radioactivity leaches from structural materials and impacts groundwater?"

If the answer is Yes: Alternative Action 1 is to conclude that the site does not satisfy release criteria and additional actions are required up to and including additional remediation and repeating FSS activiites.

If the answer is No: Alternative Action 2 is to conclude that the site satisfies criteria and may be backfilled and released for the intended land use.

The decision statement 2 is: FSS (does or does not) demonstrate that residual ROC concentrations in and below the basement structure can leach to and unacceptably impact groundwater, and therefore additional actions (are or are not) required prior to releasing the site. Because the dose criterion is based on exposures from all (in situ and ex situ) sources and exposure pathways, the licensee should also acount for the possibility of some materials being excavated and distributed across the surface and some materials remaining in place but at contamination levels that could unacceptably impact groundwater.

This leads to a third, combined decision statement:

The decision statement 3 is: FSS (does or does not) demonstrate that residual ROC concentrations in and below the basement structure can produce a combined dose above the 0.25 mSv/y (25 mrem/yr) dose limit from all site sources combined, and therefore additional actions (are or are not) required prior to releasing the site.

Case 2 Step 3. Identfy Decision Inputs—Identify Data and Information Needs
Inputs unclude the LTP/FSS; characterization data; groundwater modeling data; survey and equipment management procedures; sampling and sample management procedures; the analytical statement of work and ultimately the sample analysis results; and $DCGL_W$, $DCGL_{EMC}$, $DCGL_V$, and $DCGL_{GW}$ values for each ROC. The $DCGL_{GW}$ value considers the dose contributions for the entire structure (and underlying soils), which modelers have assessed could leach to the water table and result in an unacceptable dose to future groundwater users.

Case 2 Step 4. Define Study Boundaries—Identify Special, Temporal, and Practical Boundaries

Study boundaries include the structural floors and walls, and soils extending from the basement floor to at least the water table. Structural sample depths have been assigned to match the conceptual and dose models, while considering characterization data and the contamination depth profile. Classification boundaries are assigned based on characterization data and operational history, and SSU boundaries are assigned per standard MARSSIM guidance. Bedrock and/or the water table, if encountered below the structure floor during drilling, represents a practical boundary. Extracted cores are not always recovered in whole (recovery < 100 percent), representing a potential data gap, so boreholes will be scanned to determine if and at what depth contamantion is present. The project schedule outlines temporal boundaries.

Case 2 Step 5. Develop A Decision Rule—Specify Parameters for Making Decisions
The licensee is required to assess whether average residual ROC concentrations (μ_S) exceed average reference area concentrations (μ_R) by $DCGL_V$ and $DCGL_{GW}$ values, and whether elevated areas could reasonably result in a volume of materials that exceed $DCGL_{EMC}$ values, if brought to the surface during a small-scale excavation. Because the project has both a decision problem (concentrations statistically below $DCGL_V$ values) and an estimation problem (total inventory contributing to the groundwater dose below $DCGL_{GW}$ values), two decision rules are required.

Decision rule 1 is: *If* the FSS demonstrates that residual average and elevated area ROC concentrations in the structure can produce a dose above the 0.25 mSv/y (25 mrem/yr) dose limit, *then* additional action, up to and including additional source removal and repeating the FSS, will be conducted, *else* the decision is that the structure satisfies criteria and may be released for the intended future land use, depending on the outcome of decision rule 2.

Decision rule 2 is: *If* the FSS demonstrates that residual ROC concentrations in and below the structure can produce a water-dependent dose above the 0.25 mSv/y (25 mrem/yr) dose limit, *then* additional action, up to and including additional source removal and repeating the FSS, will be conducted, *else* the decision is that the structure and subfloor soils satisfy criteria and may be release for the intended land use, depending on the outcome of decision rule 1.

That is, in order for the structure to be released, the licensee should demonstrate that 1) materials in any SSU does not contain enough residual radioactivity to produce an unacceptable dose assuming materials are excavated and distributed across the surface, and 2) remaining contamination does not represent an unacceptable threat to groundwater.

Given the potential threat from both excavated and un-excavated materials:

Decision rule 3 is: *If* the FSS demonstrates that residual ROC concentrations in and below the structure can produce a total dose above the 0.25 mSv/y (25 mrem/yr) dose limit from all site sources combined, *then* additional action, up to and including additional source removal and repeating the FSS, will be conducted, *else* the decision is that the structure satisfied criteria and may be released for the intended land use.

Case 2 Step 6. Specify Performance Or Acceptance Criteria—Specific Limits on Decision Errors (Decision Problem) or Develop Performance Criteria (Estimation Problem)
A statistical test will be used to determine whether or not residual concentrations in any SSU exceed $DCGL_V$ values. The licensee selects Scenario A where the DCGL is used as the substantial difference. Some of the ROCs are present in background, but the licensee has determined that associated background concentrations are a small fraction of respective $DCGL_V$

values. Therefore, the licensee decides to simplify the process and ignore background concentrations, and thus selects the Sign test. For this aspect of the project:

H_0 = residual concentration exceed DCGLs; $\mu_S > DCGL_V$ ($\mu_R = 0$)
H_A = residual concentration are less than or equal to DCGLs; $\mu_S \leq DCGL_V$
Type I error (α) = 0.05 (95% confidence)
Type II error (β) = 0.05 (95% power)

Because there are multiple ROCs and assocaciated DCGLs, the $DCGL_V$ used to estimate the number of samples in structural SSUs is normalized (set to 1). Based on characterization data, the weighted expected mean and standard deviation concentrations are 0.2 in Class 2 SSUs. The relative shift for Class 2 SSUs is four, which is conservatively adjusted down to three. MARSSIM Table 5.5 shows that 14 statistical samples are required in Class 2 SSUs (including the 20 percent increase for unusable samples). For Class 1 SSUs the expected mean concentration is 0.4 and the expected standard deviation is 0.5. The relative shift for Class 1 SSUs is 1.2, and MARSSIM Table 5.5 shows that 23 statistical samples are required (including the 20 percent increase for unusable sample).

The project should also demonstate that residual concentrations in and below the structure will not produce an unacceptable impact to groundwater. The licensee concludes that 14 statistical samples per Class 2 SSU and 23 statistical samples per Class 1 SSU will be more than sufficient for estimating the total inventory for the overall structure contributing to the groundwater pathway dose. Core sample through the floor to the underlying soils will also be required to estimate contamination levels under the structure, if any, which is addressed under DQO Step 7.

Case 2 Step 7. Optimize The Design—Develop the Sampling and Analysis Plan
The VSP code is used to distribute required samples per SSU using a systematic grid with a random starting point. The licensee issues a technical basis document justifying the use of in situ gamma spectrometry in place of discrete (volumetric) sampling. To verify that method works throughout the decommissioning project, the licensee will also collect volumetric samples for laboratory analysis at least at a fixed percentage of the SSU locations, ideally targeting locations where the in situ measurement system identifed residual radioactivity although a percentage should also be collected where the in situ measurement did not identify residual radioactivity to ensure such measurements are true negatives. At each sample location, a static gamma measurement is collected above/beside the location (for information that may be used to correlate data) and in structural sample boreholes, when collected (to determine if contamination increases with depth). Individual sample depth and volume has been established to match the conceptual/dose model (for depth) and analytical laboratory requirements (for mass/volume). Volumetric samples will be collected using standard methods.

All (100 percent) of the accessible areas will be scanned using a combination of large area detector (e.g., gas proportional or scintillators) and NaI detectors, as access permits. Surveyors are instructed to listen and flag locations that exceed the project-specific investigation level. The licensee will use professional judgment to determine which, if any, of the flagged locations will be sampled to assess a potential threat to EMC or $DCGL_{GW}$ limits. Walls that cannot be safely reached by surveyors can be scanned with mechanical assistance (e.g., and boom lift) or be subject to composite sampling.

The licensee will also evaluate the use of in situ spectrometry at difficult to access or inaccessible locations, assuming the technical basis demonstrates that shorter count times (than those at statistical sample locations) justify replacing traditional scanning methods. Discrete sources such as embedded piping and transfer canals will be scanned and sampled as practicable using pipe crawlers, scrapers, etc. If discrete sources are not threats to EMC or $DCGL_{GW}$ thresholds, the licensee will evaluate methods to fix residual contaminants in place via grouting or other means. Threats to EMC of $DCGL_{GW}$ thresholds will be remediated and reassessed, as required.

To assess potential contamination below the foundation, the licensee will use an adaptive cluster approach, noting that the licensee can also select judgmental locations to fill (spatial or other) data gaps and investigate potential pathways not represented via the random selection process. Specifically, the adaptive cluster approach can be implemented by augmenting the systematic gid used to distribute random samples. The VSP code is used to position secondary node equidistant between primary nodes, as illustrated in Figure 2.13.[2] The licensee will scan each extracted (primary) core using hand-held detectors and will perform down-hole gamma scans to help identify and delineate residual radioactivity. If residual radioactivity is identified above the investigation level at a primary location, cores will be extracted at adjacent secondary nodes.

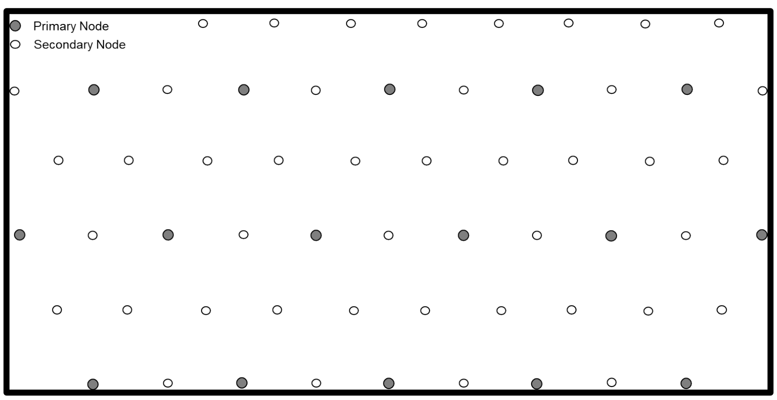


Figure 2.13 Example Systematic Grid Illustrating Primary Nodes (for Statistical Testing) and Secondary Nodes (for Potential Adaptive Cluster Sampling)

2.8.3. Case 3—Example DQOs for Borrow Soils

Case 3 Step 1. State the Problem—Define the Problem that Necessitates the Study
The large excavation and structure described in Cases 1 and 2, respectively, will ultimately be backfilled with approved materials, as illustrated in Figure 2.14. The licensee has identified a borrow site with sufficient materials to satisfy the demand. The borrow site has no history of radiological operation, is upwind and upgradient of process-related activities, and has likely not been impacted by other (neighboring) radiological facilities. Again the licensee recognizes that the characterization of borrow materials does not follow the MARSSIM approach, and in this case little if any of the MARSSIM method can be directly applied. Per stakeholder agreement, the licensee should ultimately demonstrate that key radionuclide concentrations from the borrow site are indistinguishable from background.

[2] See VSP help on adaptive sampling at https://vsp.pnnl.gov/help/Vsample/Design_Adaptive_Cluster.htm.

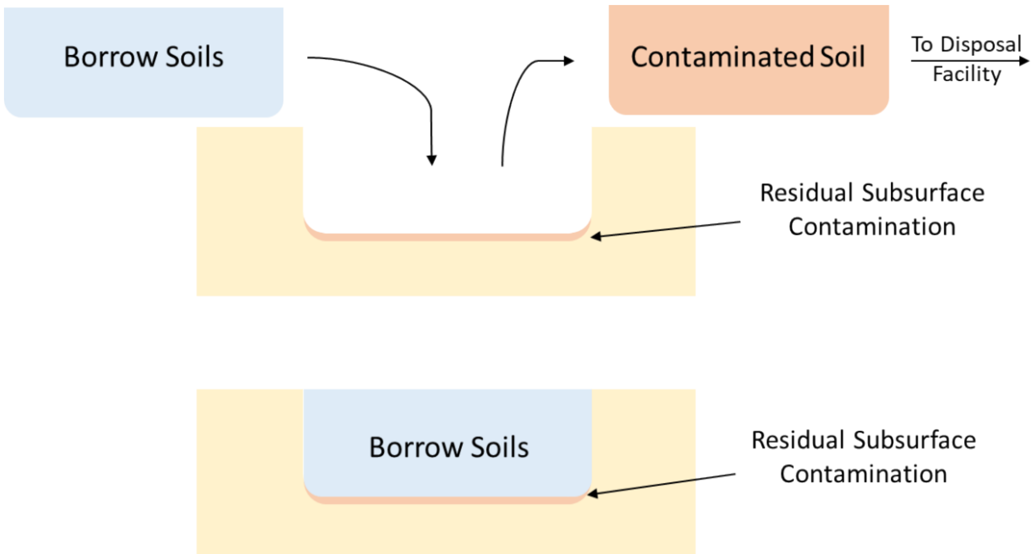


Figure 2.14 Example Use of Borrow Materials

Case 3 Step 2. State the Study Goal—State How Data Will Be Used to Meet Objectives
The principle study question is, "Does the survey demonstrate that radionuclide concentrations in borrow soils are not greater than reference areas concentrations?"

If the answer is Yes: Alternative Action 1 is to conclude that the borrow site satifies criteria and may be used as a source of backfill soil.

If the answer is No: Alternative Action 2 is to conclude that the borrow site does not satify criteria and may not be used as a source of backfill soil—the licensee should find another site.[3]

The decision statement is: The survey (does or does not) demonstrates that radionuclide concentrations at the borow site are statistically no greater than reference area concentrations, and therefore (can or cannot) be used as a source of backfill soil.

Case 3 Step 3. Identfy Decision Inputs—Identify Data and Information Needs
Inputs include the LTP/FSS; characterization data; survey and equipment management procedures; sampling and sample management procedures; and the analytical statement of work.

Case 3 Step 4. Define Study Boundaries—Identify Special, Temporal, and Practical Boundaries
Study boundaries include the potential borrow site with sufficient materials to meet backfill demands. If approved for use, heavy excavators will be used to extract soils from different depths, so the licensee will have to decide how to compare results (a population for specific depth intervals or one population over all depths). The licensee will also have to decide how to monitor for changing conditions by, for example, scanning and/or sampling during backfill operations. Finally, the project schedule outlines temporal boundaries.

Case 3 Step 5. Develop A Decision Rule—Specify Parameters for Making Decisions

[3] Alternatively, the licensee can assess the added dose associated with the reuse soils.

The licensee is required to assess whether average concentrations (μ_S) at the borrow site exceed average reference area concentrations (μ_R), presuming borrow materials will add no additional activity to the site being backfilled.

The project decision rule is: *If* the survey demonstrates that radionuclide at the borrow site is less than or equal to reference area concentrations, *then* soils from the site can be used as a source of backfill, *else* the licensee will be required to identify a different borrow site.

Case 3 Step 6. Specify Performance Or Acceptance Criteria—Specific Limits on Decision Errors (Decision Problem) or Develop Performance Criteria
A statistical test will be used to determine whether potential borrow site concentrations exceed reference area concentrations. The licensee selects Scenario B' to determine if population means are statistically different. Scenario B' relaxes the burden of proof for demonstrating that the borrow is acceptable. Stakeholders agree that the consequence of incorrectly concluding the off-site borrow is unacceptable outweighs the potential consequences of borrow concentrations exceeding the reference area. For now (see DQO Step 7), the WMW test is selected to test the data. For this project:

H_0 = borrow site concentrations are no higher than reference area concentrations; $\mu_S \leq \mu_R$
H_A = borrow site concentrations are higher than reference area concentrations; $\mu_S > \mu_R$
Type I error (α) = 0.20 (80 percent confidence)
Type II error (β) = 0.10 (90 percent power)

In order to estimate the number of samples required to perform the test, stakeholder should define the width of the gray region (Δ), or the expected difference between mean concentrations. That is, by what amount does μ_S have to exceed μ_R before the test rejects the null hypothesis? After some deliberation, stakeholders agree to $\Delta = \sigma_R$. Using Equation 2.5 in Section 2.5, the required number of samples is 12, thus 12 in the borrow area and 12 in the reference area.

Case 3 Step 7. Optimize The Design—Develop the Sampling and Analysis Plan
The VSP code is used to distribute 12 sample locations across each area using a quasi-random approach to avoid clustering. A core of appropriate depth is collected from each location, which will be homogenized by the laboratory prior to analysis. Prior to completing the WMW test, each population will be tested for normality and to determine if variances are statistically different. If both populations are normal and its variances are similar, data will be subject to the two-sample t-test, which adds power to the test. If either population is non-normal, or if population variances are significantly different, the licensee will proceed with the WMW test.

The acceptance of borrow materials is primarilly based on testing mean concentrations, as demonstrated, although borrow materials will still be subject to scans. Multiple options are available to the licensee including scanning in situ (prior to excavation), in a laydown area (by spreading soil over an area and then scanning), and by using a conveyor system (using preset alarms to direct soil into use/do-not-use stockpiles). These and other options can also be used in combination, noting that any of these scanning methods are used to identity small area/volume or materials with relatively elevated activity, including naturally-occurring materials. The licensee establishes QC measures to scan a specified percent of the containers (e.g., truckloads) either in situ or in laydown area to ensure the site continues to produce non-radiologically-impacted material. The licensee also established QC measures to collect a composite samples from a specified number of containers to ensure the borrow concentrations are within established tolerances.

2.9 Overlap of FSS and RASS

Section G.3.2, of NUREG-1757, Volume 2, Rev. 2 contains guidance on surveys of open excavations and materials planned for reuse as backfill. The guidance discusses the access opportunity afforded by an open excavation. Because of this access, the NRC expectation is that a RASS of the open excavation will be performed to the quality of an FSS prior to backfill to support license termination. The guidance also discusses the survey of excavation materials in situ for the purpose of informing classification as well as making decisions regarding the disposition path of the material (e.g., disposal of the material as waste or reuse of the material as backfill); or the survey of the backfill materials ex situ, as described in more detail in this ISG in Sections 2.6 and 2.7. NUREG-1757, Vol. 2, Rev. 2 also discusses the situation where separate DCGLs (e.g., $DCGL_{V\_S}$/$DCGL_{V\_GW}$, and $DCGL_{V\_R}$ in this ISG) are derived for different surface and subsurface layers and the cumulative dose from all layers is assessed. However, NUREG-1757, Volume 2, does not address the issue of when a licensee presents information from an FSS following backfill of an open excavation that may overlap the RASS of the open excavation prior to backfill.

The RASS of the open excavation should be of sufficient quality to use as the FSS for subsurface materials below the excavation. However, in certain situations, licensees may choose to perform an FSS of the backfilled excavation from the surface down below the excavation bottom, if residual radioactivity is present in reuse soils to assess compliance with license termination rule criteria for the final configuration of residual radioactivity present in the survey unit. Reasons for performing an FSS after backfill may also include difficulties in tracking (i) the location/elevations of materials during excavation activities, (ii) the transfer of excavated soils to stockpile locations after excavation, and (iii) the placement of stockpiled material back into the excavation. FSS of the total thickness of residual radioactivity (reuse materials and in situ materials remaining below the excavation) may also facilitate demonstration of compliance with release criteria when multiple contaminated layers or strata cumulatively contribute to dose as described below.

In these cases, the RASS and FSS should be evaluated as two independent surveys, and the RASS should be the primary survey to support release of the subsurface materials below the excavation, while the FSS performed at the surface should focus on scanning the surface materials and reuse soils used to fill the excavation above the excavation floor to support release of those materials. Operational DCGLs (i.e., DCGLs established at a fraction of the dose limit to account for multiple contaminated media) can be used to ensure that the total dose from the reused soils and the residual radioactivity remaining at the bottom of the excavation meet the release criteria.[4] It is expected that the licensee would not proceed with backfilling an excavation unless the RASS (performed to the quality of an FSS) supports release of the subsurface materials. Therefore, if the results of an overlapping surface FSS reveal potential residual radioactivity at depth that does not meet release criteria, then the licensee would need to explore the cause for inconsistencies between the two sets of survey results. The licensee should consult the NRC for additional actions that could be taken to inform the need for additional remediation, or to demonstrate compliance with release criteria.

In some cases, for safety or other reasons, the excavation is backfilled prior to performance of a RASS to the quality of an FSS. The licensee should attempt to plan for these situations in the final status survey plan to the extent practical and consider the roles of the RASS versus the

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[4] Sections 5.5.2 and 7.1.1 discuss the use of either single or multiple DCGLs for surface and subsurface DCGLs and the limitations of each.

FSS to ensure data are collected of sufficient quality to support decision-making. For example, RASS may be used to support identification and removal of elevated areas and inform the need for additional remediation, while the FSS could be relied on to demonstrate compliance with release criteria. Guidance is provided in Section 2.5 on consideration of survey/sampling requirements to support decision-making for surface and subsurface materials and decision units as part of the DQO process. Examples are provided in Section 2.8.

As explained in NUREG-1757, Volume 2, Rev. 2, in some cases multiple DCGLs are derived, and the survey design should ensure collection of data of sufficient quality to demonstrate compliance with release criteria. Dose modeling should consider sensitivity of the results to key source parameters (e.g., source area, thickness, and depth) to ensure that the dose is not underestimated. For example, depth discrete sampling may be needed to ensure that concentrations are not diluted in a larger thickness of residual radioactivity (greater than around 15 cm), if surface concentrations dominate the dose. If the plant ingestion pathway dominates the dose, then average concentrations within the expected root depth may be acceptable for use. If the groundwater pathway dominates the dose, the total activity at depth may be most important to dose. Various approaches discussed in this chapter can be used to ensure that the comparison of survey results to DCGLs provides an adequate basis for demonstrating compliance with radiological criteria for license termination.

2.10 Role of Confirmatory Surveys and Lessons Learned Associated with Subsurface Surveys

Confirmatory surveys (or independent verification (IV))[5] has been an integral part of the regulatory process to help ensure the licensee has met all decommissioning commitments and to provide reasonable assurance that property release actions meet requirements. At a minimum, confirmatory surveys help ensure that the radiological licensee's procedures, instruments, field and analytical data, and documentation are adequate for demonstrating compliance with the LTP. Perhaps most importantly, confirmatory surveys enhance credibility and build stakeholder trust that released property poses minimal risk to the public—a paramount concern for the NRC and other stakeholders.

The confirmatory survey process is performed by either members of the cognizant regulatory agency or as otherwise assigned to independent contractors or other conflict-of-interest-free entities. In general, confirmatory survey personnel should demonstrate the capability to successfully perform the necessary verification activities associated with the following:

- Establishing and implementing protocols for multi-media sampling,
- Managing and operating radiation instrumentation,
- Collecting radiation measurements and radiological samples,
- Interpreting radiation measurement and laboratory analytical data, and
- Reviewing and preparing release documents.

There are significant economic, stakeholder, and long-term risk mitigation benefits that result from the proper and timely implementation of confirmatory surveys. Major benefits include:

- Avoiding delays and cost increases by identifying issues early in the release process,

[5] IV is a term used by other federal agencies and is interchangeable with the term "confirmatory surveys" in this ISG.

- Ensuring the licensee’s plans, procedures, and reports are technically sound,
- Providing real-time corrective actions if areas of concern are identified,
- Issuing accurate and defensible documentation to validate compliance with release requirements and avoiding possible future problems, and
- Preventing an improper property release.

The intent of the confirmatory survey effort is not to duplicate or simply repeat the licensee’s methods but rather to validate multiple aspects of the site’s final status condition as presented in the licensee’s documentation. The confirmatory survey activities are unique for each site and are determined via the DQO process as typically documented in a confirmatory survey plan. For example, confirmatory survey actions may include a relatively small effort limited to technical reviews and assessments of licensee procedures and processes or an independent field investigation including the collection of field measurements and environmental media samples, and subsequent analysis of field and laboratory analytical data. The confirmatory survey effort may involve a variety of principal study questions (PSQs) that include either statistical or judgmental assessments or both based on site-specific, case-by-case conditions. For example, a PSQ for gamma radiation scans may be necessary to assess a licensee’s ability to identify elevated areas. A PSQ could call for side-by-side measurements/samples with the licensee or the collection of a completely independent sample population to estimate and compare various statistical parameters. That is, the graded approach is applied to confirmatory survey to scale the effort commensurate with the scope, complexity, and risk associated with the release action.

Decades of confirmatory survey activities across a wide range of site and radiological conditions have generated lessons learned applicable to subsurface decision units. These lessons learned include but are not limited to the following:

- Dose modeling to derive clean-up levels assumed a shallow depth of residual radioactivity in the basement floor slab. The licensee collected deep core samples that diluted concentrations to values below the clean-up levels derived from dose modeling—the depth interval used in the survey was inconsistent with the assumed depth of residual radioactivity in the exposure or dose model.
- Reuse soil piles were inadequately sampled and assessed for HTDs prior to use as backfill.
- Confirmatory survey revealed an unacceptably high false negative rate leading to inadequate statistical power for assessment of off-site borrow material.
- Confirmatory survey revealed inadequate detector calibration for the radionuclide mixture in the technical basis document for surface activity measurements within embedded process pipes.
- Confirmatory survey revealed inadequate FSS of subsurface soil areas susceptible to cross contamination during demolition activities.
- Inadequate documentation of the status of subsurface areas from the decommissioning contractor to the NRC was noted in a confirmatory survey.
- Licensees have developed an inadequate process for identifying elevated areas when performing in situ gamma radiation measurements (e.g., no complimentary surface scans were conducted to identify elevated areas).
- Confirmatory survey revealed a lack of validation of HTD ratios following remedial activities in basement structures or for material planned to be rubblized and reused as backfill.
- Finally, backfilling of SSUs has occurred prior to the opportunity for NRC to conduct a confirmatory survey.

Chapter 7 discusses examples in greater detail. However, the above situations led to inefficient decision making as both licensees and the NRC had to utilize additional resources to ensure that the final residual radioactivity at the site was known with the proper level of confidence for the license termination decision.

3. DOSE MODELING CONSIDERATIONS FOR SUBSTRUCTURES LOCATED ABOVE AND BELOW THE WATER TABLE

The RESRAD (-ONSITE) Version 6[6] conceptual model considers sources located in a contaminated zone in the unsaturated zone (i.e., RESRAD-ONSITE Version 6 does not consider sources located in the saturated zone). Appendix E of the RESRAD-ONSITE Version 6 User's Manual (ANL 2001) contains information on calculation of dilution factors for the well water in the saturated zone. Some decommissioning sites have used RESRAD-ONSITE to model release of residual radioactivity from substructures located in the unsaturated zone and flow and transport to a well located in the saturated zone. Because substructure walls and floors may impede flow and a bathtub effect may be realized, the saturated zone conceptual model adopted in the RESRAD-ONSITE Version 6 may not apply. Nonetheless, NUREG-1757, Volume 2, Rev. 2, Appendix J, provides guidance on how the RESRAD-ONSITE computer code can be conservatively used for assessing contaminant release from substructures located in the unsaturated zone. Section 3.1 of this ISG provides additional guidance and examples demonstrating the use of the RESRAD-ONSITE computer code for sources associated with substructures located in the unsaturated zone.

Starting in Version 6.5, RESRAD-ONSITE considers sources located above, straddled across, and located below the water table (with the source located at the top of the water table; see Figure 3.1). The equations in Appendix E of the RESRAD-ONSITE Version 6 User's Manual for calculation of dilution factors were expanded to handle these various source configurations considering vertical and horizontal flow vectors in the saturated zone. Because many basement substructures are located below the water table, these new source configurations have been used in LTP submittals to calculate the dose associated with those substructures located in the saturated zone. However, due to the differences in conceptual models, additional support may be needed for using RESRAD-ONSITE to derive DCGLs or calculate dose from sources associated with substructure walls and floors located partially or fully in the saturated zone. Section 3.2 provides guidance and examples demonstrating the application of the RESRAD-ONSITE computer code for evaluating substructure sources located wholly or partially in the saturated zone.

3.1 Use of RESRAD-ONSITE for Sources Located in the Unsaturated Zone

The RESRAD-ONSITE User's Manual for Version 6 (ANL 2001) provides information on the mass balance and non-dispersion saturated zone models available in the RESRAD-ONSITE computer code (see Section E.3.1.3. "Dilution Factor" and Equations E.26, E.27, and E.28, and Figure E.1 in the RESRAD-ONSITE Version 6 User's Manual; and NUREG-1757, Volume 2, Rev. 2, Appendix I, Section I.5.3.6). Because the non-dispersion model results in lower concentrations, the mass balance model is typically acceptable without further justification, while use of the non-dispersion model may require additional support. NUREG-1757, Volume 2, Rev. 2, describes the four cases implemented in the non-dispersion model when the source or contaminated zone is in the unsaturated zone (see Table I.9 and Figures 5.3 and 5.4 in NRC (2020)) and provides guidance on when the non-dispersion model may be acceptable for use.

[6] RESRAD Version 6 software is hereafter referred to as RESRAD-ONSITE Version 6 to differentiate between RESRAD-ONSITE and RESRAD-OFFSITE computer codes.

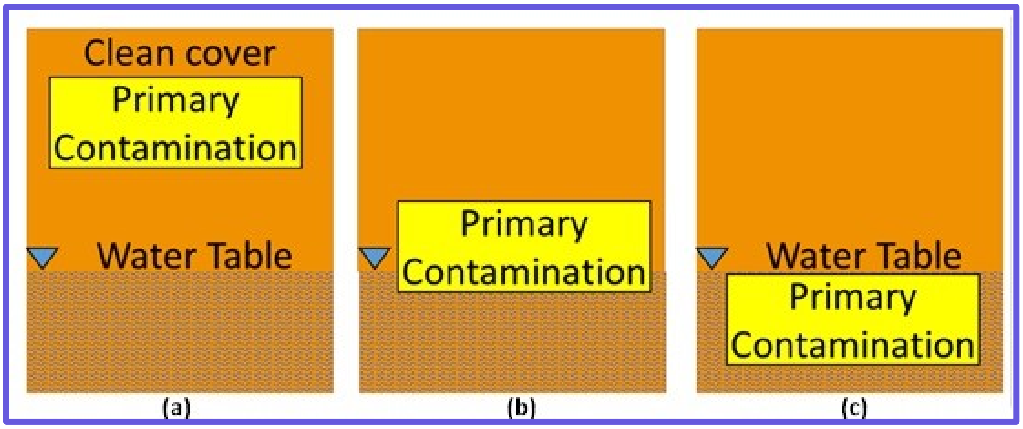

Figure 3.1 Locations of Primary Contamination. Image Credit: Figure 2-1, NRC 2020b.

RESRAD-ONSITE Version 6 considers sources located in the unsaturated zone only. This section evaluates the use of RESRAD-ONSITE saturated zone models for the case where the source is in the unsaturated zone. The non-dispersion model defaults to the mass balance under certain conditions and would generally be acceptable for use in those cases. The two cases are (i) when the pumping width is larger than the contaminated zone width and the depth of the plume is less than the depth of the well (the dilution factor is similar to the mass balance model and is based on the volumetric flow rate through the contaminated zone divided by the well pumping rate), and (ii) when the width of the contaminated zone is larger than the pumping diameter and the plume depth is deeper than the well intake depth (in which case the dilution factor is 1 representing the case where everything going to the well is contaminated). See discussion in Section I.5.3.6 of NUREG-1757, Volume 2, Rev. 2 (NRC 2022).

NUREG-1757, Volume 2, Rev. 2, Appendix J, provides guidance on how the RESRAD-ONSITE computer code can be used to model sources associated with substructures located entirely above the water table despite potential differences between source release and flow conditions in a reactor substructure versus the soil system which is conceptualized in the RESRAD-ONSITE computer code. For example, although RESRAD-ONSITE does not consider surface rinse or diffusion-limited release of residual radioactivity from a concrete structure and does not consider a contaminated zone with a hydraulic conductivity that is lower than the infiltration rate leading to a “bathtub” effect, simplifying assumptions can be made to allow use of RESRAD-ONSITE code to derive DCGLs for basement substructures. Although the walls and floor of a basement substructure may impede flow to the groundwater aquifer, the analyst can assume that the concrete structure does not impede flow thereby hastening the release of residual radioactivity to the water table aquifer. Furthermore, residual radioactivity on the walls of the structure can be assumed to be associated with the substructure floor also decreasing the distance from the source to the water table and the time for residual radioactivity to be transported to the water table aquifer. These simplifying assumptions are expected to be reasonably conservative for calculation of doses from the groundwater pathway from sources associated with basement substructures. If more realistic source term and flow modeling is needed to demonstrate compliance, more sophisticated groundwater flow and contaminant transport models can be used.

After the residual radioactivity released from the contaminated zone is transported through the vadose zone and enters the saturated zone, RESRAD-ONSITE calculates the dilution factor in the non-dispersion model using the parameters and equations described in Figures 3.3 and 3.4.

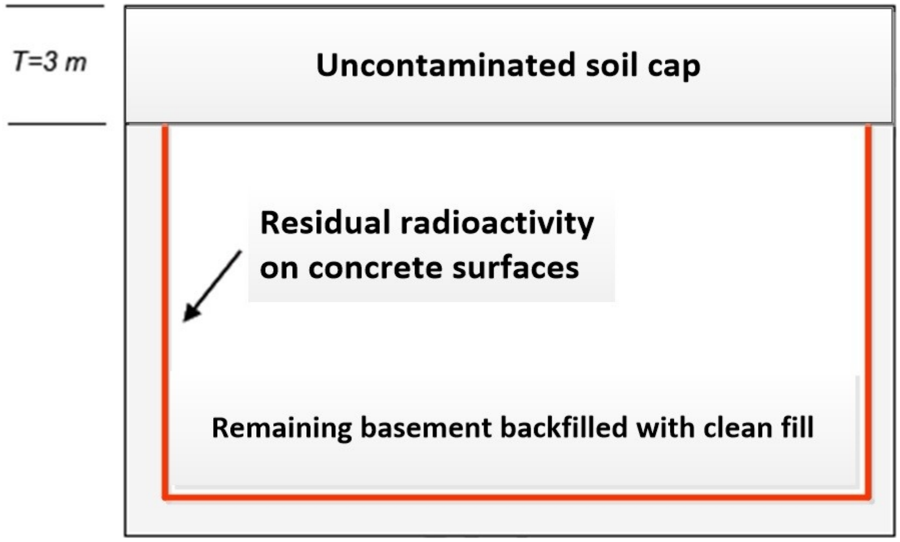

Figure 3.2 Example of Contaminated Basement Backfilled with Clean Fill. Image Credit: Figure J.2, Appendix J (NRC 2022).

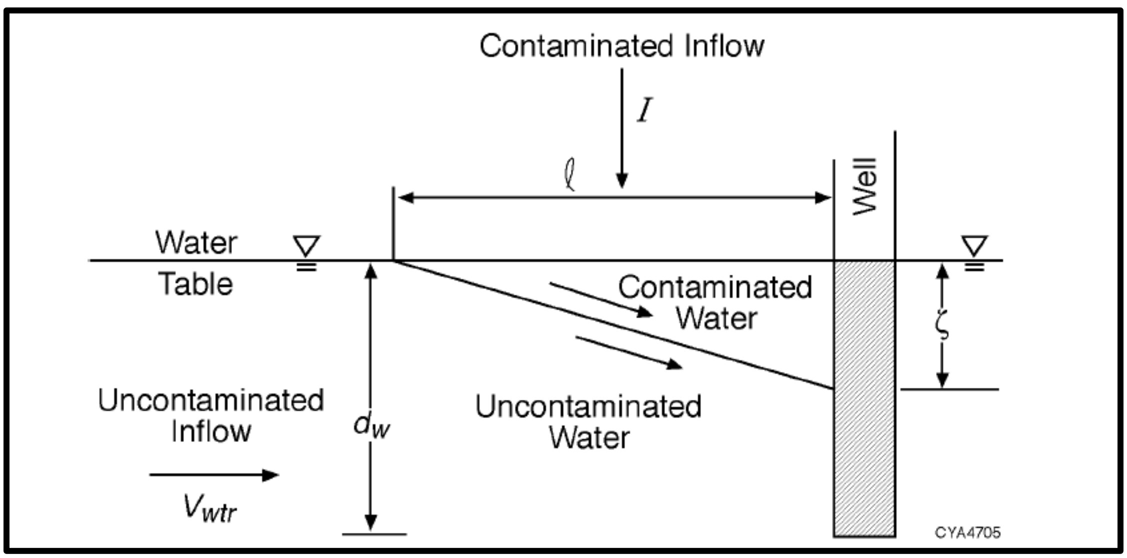

Figure 3.3 Saturated Zone Conceptual Model in RESRAD-ONSITE Version 6. Adapted from Figure E.1 in the RESRAD 6 User's Manual (ANL 2001).

Where:

ζ is $(I / V_{wfr})\,\ell$ or the distance from the water table to the lower boundary of contamination in the aquifer at the downgradient edge of the contaminated zone (m),

I is the infiltration rate (m/yr)

V_{wfr} is $K_s^{(sz)}J_x$ or the water flow rate per unit cross-sectional area in the SZ (Darcy velocity, m/yr)

$K_s^{(sz)}$ is the saturated hydraulic conductivity of the saturated zone (m/yr),

J_x is the hydraulic gradient in the flow (x) direction (dimensionless),

ℓ is the length of the contaminated zone parallel to the hydraulic gradient (maximum distance from the upgradient edge to the downgradient edge parallel to the hydraulic gradient),

d_w is the distance of the well intake below the water table,

$T_{\ell,i}$ is $p_e^{(sz)} R_{d,i}^{(sz)}$ (ℓ / V_{wfr}) or the time for the ith principal radionuclide to be transported from the upgradient edge to the downgradient edge of the saturated zone (yr),
$p_e^{(sz)}$ is the effective porosity of the aquifer (dimensionless), and
$R_{d,i}^{(sz)}$ is the retardation factor for the ith principal radionuclide in the saturated zone (dimensionless)

For the subsurface case, the following four cases apply (see RESRAD Version 6 User's Manual, Equation E.27):

$$DF = \frac{\zeta}{d_w} \, when \, d_r \leq \frac{A}{l}, \zeta < d_w \quad \textbf{Case 1}$$

$$= \frac{A\,I}{U_w} \, when \, d_r > \frac{A}{l}, \zeta < d_w \quad \textbf{Case 2}$$

$$= 1.0 \text{ when } d_r \leq \frac{A}{l}, \zeta \geq d_w \quad \textbf{Case 3}$$

$$= \frac{A\,I\,d_w}{U_w \zeta} \, when \, d_r > \frac{A}{l}, \zeta \geq d_w \quad \textbf{Case 4}$$

Figure 3.4 Dilution Factors for Four Non-Dispersion Factor Cases.
Image Credit: Equation E.27 in the RESRAD Version 6 User's Manual (ANL 2001)

The effective pumping diameter, d_r, in Figure 3.4 is calculated in RESRAD-ONSITE using the following equation:

$$d_r = \frac{U_w}{V_{wfr} d_w}$$

All other parameters are as they are described in Figure 3.3. The four cases listed in Figure 3.4 represent a situation where (i) contaminated water is diluted with clean water entering the well in the case that the width of the contaminated zone is larger than the pumping diameter but the plume depth is shallower than the well pump intake depth, (ii) the non-dispersion model defaults to the mass balance model with dilution from clean water due to the pumping diameter being larger the contaminated zone width, and the plume depth being shallower than the well pump intake depth (i.e., the contaminated plume water completely enters the well and is diluted in the pumping volume of the well), (iii) no dilution occurs due to the plume depth being deeper than the well intake depth and the contaminated zone width being larger than the pumping diameter (i.e., all water going to the well is contaminated), and (iv) a more complicated case where some of the plume bypasses the well (the plume depth is deeper than the well intake depth) and the width of the contaminated zone is smaller than the pumping width leading to dilution in the well. An illustration of these four cases is provided in Figure 3.5 below. For example, the blue polygon shows the pumping diameter in relation to the contaminated zone width (orange rectangle) and the orange triangle shows the depth of the plume in relation to the well intake depth below the water table (vertically oriented blue hashed pipe). Depending on whether the blue polygon (pumping diameter) is smaller or larger than the contaminated zone width shown in orange, and depending on whether the plume depth is shallower or deeper than the distance of the well intake below the water table (orange triangle extends above or below the vertical, blue hashed well screen), will determine which of the four cases apply and the amount of dilution in the well.

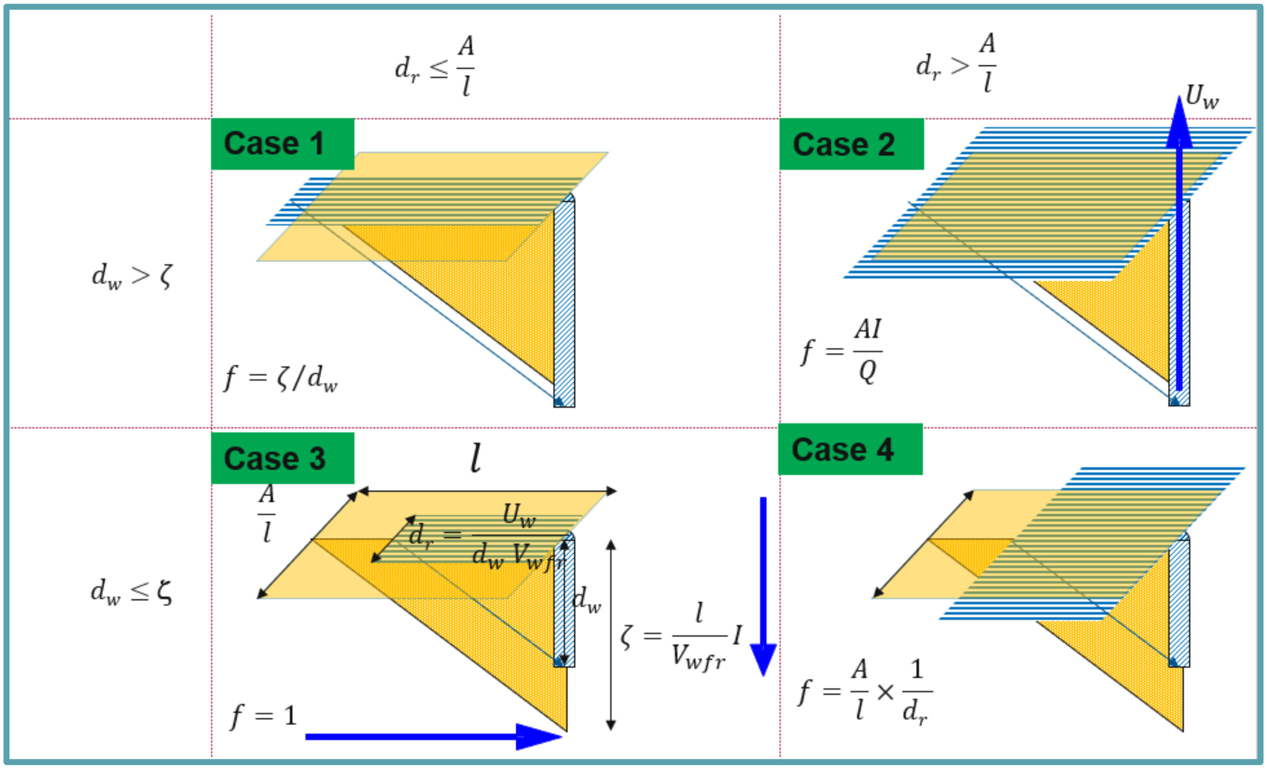

Figure 3.5 Plume (vertical orange triangle) depth, ζ, versus well intake (vertical blue hashed pipe) depth, d_w, and pumping diameter (horizontal blue hashed rectangle), d_r, versus contaminated zone width (horizontal orange polygon), *A/l*, for four non-dispersion model cases in RESRAD-ONSITE. Modified from RESRAD Training Slide.

In some cases, the RESRAD-ONSITE computer code has been used to estimate the total inventory (or activity concentration) that can remain on reactor basement walls and floors and meet the license termination rule criteria for the in situ leaching scenario. Two approaches have recently been used including (i) use of the DUST-MS computer code to model the release of residual radioactivity to the pore volume of the fill material that will be used to backfill the substructures (e.g., pCi/L (or Bq/L) in the pore water per mCi (or Bq) on the basement substructures is output from DUST-MS), or (ii) use of hand calculations to determine the concentration of residual radioactivity assumed to be directly transferred to various assumed volumes of backfill located directly next to the substructure walls or floors, up to and including the entire fill volume. In the latter case, the hand calculated concentrations are used as inputs in the RESRAD-ONSITE to define the contaminated zone source parameters to model the release and transport of the source to a well located at the downgradient edge of the contaminated zone. In both cases, RESRAD-ONSITE is used for the biosphere modeling (e.g., to determine the dose from groundwater dependent pathways). However, in the former case, RESRAD-ONSITE is only used to calculate the pathway dose conversion factor (i.e., dose per unit groundwater concentration as described in Section 4.1), while in the latter case RESRAD-ONSITE is used as it normally would be to calculate the dose based on the hand calculated soil concentrations input to the computer code. Through these series of calculations, the analysts can determine a total inventory for the basement substructure that would lead to a dose to a member of the public at the dose standard (e.g., 0.25 mSv/yr to the average member of the critical group for unrestricted release). This total inventory can be converted to a surface concentration for direct comparison to surface scan survey results of the basement substructure.

Based on review of past LTP submittals, some observations can be drawn with respect to calculation of DCGLs for basement substructures. In one example, different mixing volumes for residual radioactivity were assumed to be transferred from the cylindrical wall source located above the water table to backfill located within a certain distance of the wall (e.g., from 2.54 cm to 9 m from the wall) in sensitivity analyses and selected the most conservative dose to source ratio[7]. The total volume of the contaminated zone created from the transfer of residual radioactivity from the wall to the backfill next to the wall was the sum of the individual volumes next to the wall for the various mixing volumes/distances. Because RESRAD-ONSITE only allows input of a rectangular source geometry, this total volume was assumed to be placed at the upgradient edge of the contaminated zone with the well located at the downgradient edge. Although sources associated with smaller mixing lengths away from the cylindrical wall may resemble a donut with the well in the center of the donut hole, the source was assumed to be a solid area with the length parallel to aquifer flow twice the mixing length and assumed to be located upgradient of the well. This resulted in lengths parallel to aquifer flow between 0.05 m (2 x 0.0254 m) and 18 m (2 x 9 m) and a reduction factor in concentration between approximately 6000 and 20 (reduction factors are the inverse of the dilution factors calculated in RESRAD-ONSITE which are less than 1). The parameters used in the RESRAD-ONSITE model resulted in the conceptual model similar to case 1 in Figures 3.4 and 3.5 above where the dilution factor is calculated based on the depth of the plume in relation to the well pump intake depth from the water table surface. For the smallest length parallel to aquifer flow of 0.05 m, the plume is transported downwards only about 0.001 m versus the 6 m well pump intake depth leading to substantial dilution of about a factor of 6000. In reality, if a reactor structure is resistant to flow, then flow to the well would not be dictated by the natural groundwater flow gradient surrounding the basement substructure assumed in the RESRAD-ONSITE non-dispersion model.

Furthermore, the source geometry and the source to well geometry may not be as assumed in the calculation. Because a portion of the basement substructure was located below the water table, flow for the above portion of the reactor basement substructure may still be affected by flow conditions for the below grade portion of the substructure that is modeled separately. Therefore, benchmarking simulations using a more sophisticated groundwater model that could account for the flow conditions and source to well geometry would have been an option to provide additional support for the use of RESRAD-ONSITE to model release and flow from a basement substructure. In the example described in this paragraph, the mixing volume/length resulting in the highest dose based on sensitivity analysis was used. Furthermore, other conservative assumptions are expected to have compensated for any non-conservatism with respect to the saturated zone flow modeling (e.g., assumptions regarding release of material from the concrete structure to the backfill).

Table 3.1 also shows sensitivity analysis results for the non-dispersion model versus the mass balance model, and results with two different pumping rates in the mass balance model. The mass balance model results in higher doses in every case and for every radionuclide studied. Additionally, the sensitivity analysis with a pumping rate of 250 m^3/yr versus 986 m^3/yr shows that the larger pumping rate in the mass balance model leads to greater dilution in the well and lower dose. These results are as expected. Another important aspect of the non-dispersion

[7] Because the floor of the structure was located below the water table the floor did not contribute to the portion of the source assumed to be above the water table.

model is the consideration of radioactive decay during transport. In the mass balance model, the peak dose from the groundwater pathway is realized once the contaminant travels through the vadose zone and reaches the water table. For the non-dispersion model, there is a "rise time" that accounts for travel time of residual radioactivity from the upgradient to the downgradient edge of the contaminated zone (for case 1 and 2) or the time for residual radioactivity to migrate from the furthermost point in the contaminated zone to the bottom of the well (for case 3 and 4), which could lead to a significant reduction in the well concentration due to radioactive decay of residual radioactivity during transport to the well. Conversely, if the dose is primarily from progeny that have additional time to grow-in during transport, the well concentration and groundwater dependent pathway dose could also be higher.

In another example, a well pump intake depth below the water table of 21 m was assumed, although the parameter was found to be negatively correlated to dose. This led to a case 1 situation, with the calculated dilution factor of around 0.25 or a factor of 4 reduction in concentration. Just by changing the well pump intake depth below the water table to 5 m instead of 21 m, the dilution factor calculation was based on case 3 (or a dilution factor of 1 with no reduction in the well concentration). Therefore, care should be taken to ensure that the amount of dilution is not overestimated and that the input values of the set of parameters affecting the dilution factor are evaluated in sensitivity analysis to make sure the concentration and dose from groundwater dependent pathways are not underestimated when the non-dispersion model is used.

In summary,

- Use of the non-dispersion model may result in overestimating the amount of dilution in a well for complex flow conditions associated with basement substructure sources.
- For example, the non-dispersion model assumes a well is located on the downgradient edge of a homogenous rectangular source and that the natural groundwater flow velocity and infiltration rate dictate the plume depth; and the assumed pumping rate, well intake depth, and groundwater flow velocity determine the pumping diameter, thereby influencing the amount of dilution in the well. This may not be realistic for flow occurring within a confined structure or for different source and well geometries, and site-specific conditions.
- A more sophisticated groundwater model could be used to justify use of RESRAD-ONSITE for complex flow cases or when more realistic modeling of contaminant release, flow and transport is needed. An example is provided in the next section.
- Alternatively, the concentration in the well can be maximized to provide support for use of the RESRAD-ONSITE saturated zone model for basement substructures. An example is provided in the next section.
- Additionally, the non-dispersion model also considers rise time to a well and therefore, for relatively short-lived radionuclides, additional decay during transport to the well can also lead to significantly lower concentrations and dose, which should be considered.

Table 3.1 Example RESRAD-ONSITE Output Dose and Factor Reduction in Concentration Due to Dilution Using the Mass Balance (MB) Model versus the Non-Dispersion (ND) Model and Various Well Pumping Volumes. The gray highlighted columns show the factor increase in concentration and dose if the MB versus the ND model is used.

	Half-Life (y)	Kd (L/kg)	Basecase peak dose (ND model) mrem/yr (time of dose)	MB model peak dose (using 986 m^3/yr)	MB Dose/ Basecase Dose	MB model (250 m^3/yr)	MB Dose/ Basecase Dose
H-3	12.4	0.05	8.5E-03 (0 y)	1.2E-01 (0 y)	14	1.5E-01 (0 y)	18
Ni-63	96	147	5.6E-05 (30 y)	9.9E-04 (1 y)	17.5	1.2E-03 (1 y)	21
Co-60	5.3	9	1.8E-02 (1 y)	3.2E-01 (0 y)	17.8	3.9E-01 (0 y)	22
Eu-152	13.3	95	4E-04 (17 y)	1.3E-02 (0 y)	33	1.6E-02 (0 y)	40
Eu-154	8.8	95	6E-06 (10 y)	2.5E-04 (0 y)	42	3E-04 (0 y)	50
Cs-137	30	50	1.4E-02 (10 y)	2.4E-01 (1 y)	17	3E-01 (1 y)	21
Sr-90	29	5	3.9E-01 (1 y)	5.4 (0 y)	14	6.7 (0 y)	17
Np-237	2.1E+06	1	5.84 (0 y)	86 (0 y)	15	105 (0 y)	18

Note: 1 mrem/yr = 0.01 mSv/yr.

3.2 Use of RESRAD-ONSITE for Sources Associated with Substructures Located in the Saturated Zone

Since Version 6.5, RESRAD-ONSITE has included the capability to model sources that are partially submerged or fully submerged at the top of the water table. Like previous versions, the well pump intake is located from the top of the water table aquifer to the well pump intake depth, as specified by the analyst. Figure 3.6 illustrates the conceptual model for a submerged source.

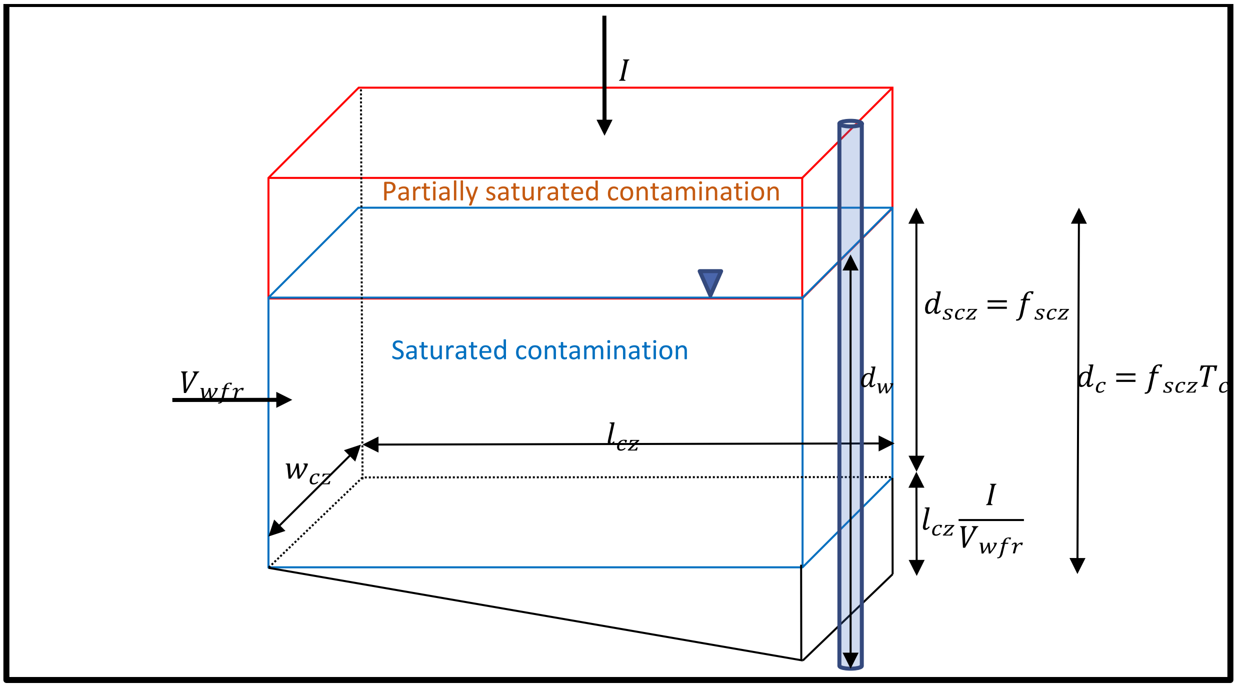

Figure 3.6 Conceptualization of the Dilution in a Well at the Downgradient Edge of a Submerged Contaminated Zone. Image credit: Figure 2 in Yu (2022).

Where:

d_c (or ζ) is the depth of contamination at the well, (m),
f_{scz} is the fraction of the contaminated zone that is submerged,
d_w is the depth of the well, (m),
$d_r = \frac{U_w}{V_{wfr}d_w}$ is the effective pumping width of the well, (m),
U_w is the pumping rate from the well, (m^3y^{-1}),
A_I is the cross section through which the infiltration enters the contaminated zone (i.e., A the area of the contaminated zone (m^2)),
A_V is the cross section through which the aquifer flow enters the contaminated zone, (m^2)
I is the rate at which water infiltrates vertically through the contaminated zone, ($m^3/m^2/y$),
V_{wfr} is the rate at which groundwater flows horizontally through the contaminated zone, ($m^3/m^2/y$),
l_{cz} is the length of the contaminated zone in the direction of the groundwater flow, (m),
w_{cz} is the width of the contaminated zone, (m),
T_{cz} is the initial thickness of the contaminated zone, (m),
d_{scz} is the submerged thickness of the contaminated zone, (m).

Although it may not be intuitively obvious, the calculation of the dilution factor is based on the vertical and horizontal flow vectors through the contaminated zone. But in this case, the contamination zone can extend wholly or partially into the water table aquifer, and both vertical and horizontal groundwater flow through the contaminated zone are considered when calculating the dilution factor. The dilution factor is obtained by multiplying these two components together (Yu 2022).

$$DF_w = DF_v \times DF_{\mathrm{h}} = min\left(\frac{d_c}{d_w},1\right) \times min\left(\frac{w_{cz}}{d_r},1\right)$$

$$DF_w = min\left(\frac{\frac{l_{cz}\, I}{V_{wfr}} + f_{scz}\, T_{cz}}{d_w}, 1\right) \times min\left(\frac{w_{cz}}{d_r}, 1\right)$$

With some algebraic manipulation, this expression can be expanded out for direct comparison to Equation E.27 in the RESRAD-ONSITE Version 6 User's Manual (ANL 2001). Like the previous model described in the Version 6 User's Manual, the cases are based on whether the depth of the contaminated plume is greater than or less than the well intake depth; and whether the width of the contaminated zone is greater or less than the well pumping diameter, leading to four combinations or cases. The main difference in the equations is that the depth of the plume can start deeper in the aquifer at time=0 years for partially or saturated sources, which should be considered in the calculations. Figure 3.7 summarizes the four non-dispersion model cases.

$$DF_w = \frac{d_c}{d_w} = \frac{\frac{l_{cz}\, I}{V_{wfr}} + f_{scz}\, T_{cz}}{d_w} \text{ when } w_{cz} \geq d_r,\, d_c < d_w \qquad \textbf{Case 1}$$

$$DF_w = \frac{d_c}{d_w}\frac{w_{cz}}{d_r} = \frac{\frac{l_{cz}\, I}{V_{wfr}} + f_{scz}\, T_{cz}}{d_w}\frac{w_{cz}}{d_r} = \frac{A_I\, I + A_V\, V_{wfr}}{U_w} \text{ when } w_{cz} < d_r,\, d_c < d_w \qquad \textbf{Case 2}$$

$$DF_w = 1 \text{ when } w_{cz} \geq d_r,\, d_c \geq d_w \qquad \textbf{Case 3}$$

$$DF_w = \frac{w_{cz}}{d_r} = \frac{A_I d_w}{l_{cz}}\frac{V_{wfr}}{U_w} \text{ when } w_{cz} < d_r,\, d_c \geq d_w \qquad \textbf{Case 4}$$

Figure 3.7 Dilution Factors for Four Non-Dispersion Factor Cases for Submerged or Partially Submerged Sources (Yu 2022).

For the reasons stated in Section 3.1, the conceptual model in the RESRAD-ONSITE computer code does not necessarily match field conditions for basement substructures. In another example, results from RESRAD-ONSITE were benchmarked against MODFLOW and MT3DMS to show that use of RESRAD-ONSITE would not lead to an underestimation of the groundwater pathway concentration and dose. The final set of parameters led to a dilution factor near 1, which ensured that the RESRAD-ONSITE well concentrations were equal to or higher compared to the MT3DMS output. This allowed the use of the RESRAD-ONSITE computer code for biosphere calculations (e.g., dose from exposure to contaminated groundwater such as use of contaminated groundwater for irrigation and livestock watering, etc.) without having to switch to potentially more resource intensive calculations with a complex groundwater flow and transport modeling coupled to a separate code for performing the dose calculations to demonstrate compliance with the release criteria.

An example calculation is provided in Table 3.2 below. Note that the analyst ended up in case 4, which led to a dilution factor of w_{cz} / d_r = 238 m / 315 m = 0.76 or a factor reduction in concentration of 1.3 times the source concentration in the saturated zone. Due to the conservatism of the dilution factor, it is a relatively easy exercise to demonstrate that a more sophisticated code such as MODFLOW coupled to MT3DMS would calculate lower concentrations in benchmarking simulations as described in more detail in Section 3.2.1.

3.2.1. Benchmarking to Support Use of Biosphere Parameters

To support the use of RESRAD-ONSITE, benchmarking simulations can also be conducted with a more sophisticated groundwater flow and contaminant transport code that is able to more realistically simulate the actual flow conditions that may be present at the decommissioning site following license termination. In an example of benchmarking, a source configuration based on instantaneous release of residual radioactivity from the basement walls and floor to a volume of backfill located 1 m away from the walls and floor with flow through the source zone that was located entirely within the saturated zone was simulated.

The source geometry assumed in RESRAD-ONSITE was simplified because the source in RESRAD-ONSITE can only be specified as a single rectangular source with a specified area and thickness. The total area of the source was assumed to be 16,700 m^2 with the source located within 1 m of the contaminated surfaces in the backfill. The length parallel to aquifer flow was assumed to be 70 m. Because this is a relatively large source and because the source thickness is equal to or greater than the assumed well depth, the concentration in a well even after considering any potential dilution was nearly the same as the calculated pore water concentration in the source zone based on the assumed distribution coefficients. This is because the dilution factor was nearly 1 (0.76 as indicated above) with only a small amount of clean water being pulled into the well. In a lower pumping rate situation, the case switches to case 3, with no dilution (a dilution factor of 1) due to a smaller calculated pumping diameter, and therefore a modest increase in the groundwater dependent pathway dose would occur. See Figure 3.8 for an illustration of an alternative approach to calculating the Case 4 dilution factor (e.g., consistent with the equation in Figure 3.7, the dilution factor can also be calculated based on the ratio of the volumetric flow rate of the contaminant to the well to the assumed well pumping rate for Case 4).

Groundwater Vistas was used for the benchmarking calculations. Groundwater Vistas contains the more sophisticated MODFLOW and MT3DMS flow and contaminant transport codes that were used to compare to the RESRAD-ONSITE results. The source geometry was conceptually like what was described above (1 meter source away from all walls and floors) with some exceptions noted. Two flow conditions were evaluated: (i) assuming walls/floors do not obstruct flow and (ii) no flow conditions (bathtub model). Several well locations were also evaluated including 1 m from the center of a wall and 1 m from the wall corner both on the upstream and downstream walls of the structure and in the center of the structure. Well depths of 4 and 9 meters were also evaluated.

The source to well concentrations in MT3DMS were compared to calculate an effective dilution factor for the MODFLOW/MT3DMS simulations, which could be compared to the dilution factors calculated using RESRAD-ONSITE. The ratios of source to well concentrations ranged from 0.11 to 0.7 for simulations run with Cs-137 and Sr-90.

Some observations from the simulations include the following:

- Positioning the well in the basement corner resulted in the highest concentration due to the proximity of the well to the source.
- Positioning the well in the basement center resulted in the lowest concentration because of the distance from the source to the well and the dilution with clean water in the well.
- Sensitivity analysis with different pumping rates did not show a significant impact on the results. This conclusion may be based on the site-specific conditions and model

assumptions (e.g., it was assumed that there was sufficient recharge to the well to support the assumed pumping rate which may not be the case in reality).

Use of a more sophisticated groundwater model to study the impact of actual versus assumed conditions is generally a valid approach to providing support for use of the RESRAD-ONSITE groundwater model. Additionally, because the well concentrations in RESRAD-ONSITE were maximized with results near the theoretical maximum values, the calculation of dilution factors to show the conservatism of the RESRAD-ONSITE analyses provides additional support for the use of RESRAD-ONSITE.

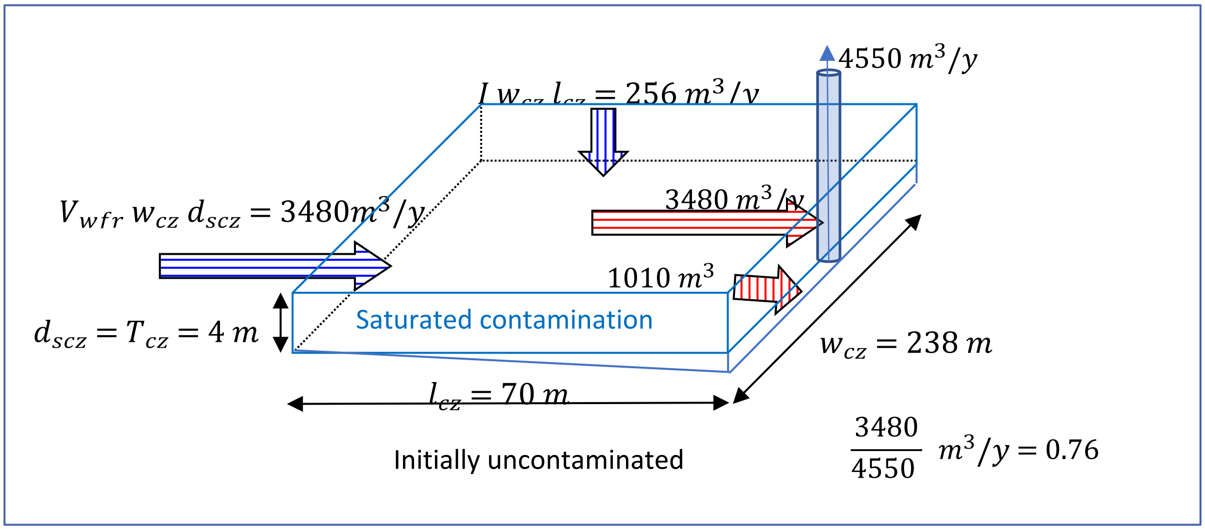

Figure 3.8 Alternative Illustration of Case 4 Dilution Factor

Table 3.2 Example Calculation of Dilution Factors for Submerged Source

Parameter	Value
A area of the contaminated zone	16,700 m^2
t_{cz} thickness of CZ	4 m
f_{scz} fraction of cz that is submerged saturated	1
l_{cz} length of contaminated zone parallel to aquifer flow	70 m
w_{cz} width of contaminated zone perpendicular to aquifer flow	**238 m** $$w_{cz} = \frac{A}{l} = \frac{16{,}700\ m^2}{70\ m} = 238\ m$$
$\frac{dh}{dz}$ hydraulic gradient	8.4E-04 m/m
K_{sat} saturated hydraulic conductivity	4,350 m/yr
V_{wfr} darcy velocity	**3.6 m/yr** $v_{wfr} = \frac{dh}{dz} \times K_{sat} = 8.4E-04 \times 4350\,\frac{m}{yr} = 3.6$
***I*, infiltration rate**	**0.06 m/yr** $I = (1 - C_e)[(1 - C_r) \times P_r + Irr] = (1 - 0.87)[(1\ \ 0.63) \times (0.7$ **C_e=evaporation coefficient** **C_r=runoff coefficient** **P_r=precipitation rate**
d_w well pump intake depth below water table	4 m
U_w well pumping rate	**4,550 m^3/yr**
d_r pumping diameter	**315 m** $$d_r = \frac{U_w}{v_{wfr} \times d_w} = \frac{4550\ m^3/yr}{3.6\,\frac{m}{yr} \times 4\ m} = 315\ m/yr$$
d_c depth of contamination at the well	**5.16 m** $d_c = \left(\frac{I}{v_{wfr}} \times l\right) + (t_{cz} \times f_{scz}) = \left(\frac{0.06\,\frac{m}{yr}}{3.6\,\frac{m}{yr}} \times 70\right. \quad + (4\ m \times 1)$
dilution factor	**Case 4** $$\frac{w_{cz}}{d_r} = \frac{238\ m}{315\ m} = 0.76$$

Note: Parameters in bold are calculated values.

3.3 <u>Support for Risk-Significant Subsurface Parameters Such as K_d</u>

3.3.1. Introduction

Recently, NRC staff have received inquiries regarding the potential need for additional support of risk-significant parameters, such as K_d in Appendix I of updated guidance NUREG-1757, Volume 2, Rev. 2 (NRC 2022). The distribution coefficient or K_d is one of the important parameters to dose owing to its influence on leach and transport rates in the environment. The K_d parameter describes the distribution of radionuclides between the solid and aqueous phase, with lower K_ds indicating a preference for radionuclides in the aqueous phase and faster transport rates or higher concentrations in groundwater. In recent meetings, it appeared that decommissioning licensees interpreted NRC guidance to mean that increased justification was needed to use the parameter distribution functions (or pdfs) in the "Data Collection Handbook to Support Modeling Impacts of Radioactive Material in Soil and Building Structures," ANL/EVS/TM-14/4 (Yu et al. 2015), including the need for site-specific values (e.g., K_ds derived from laboratory analysis). The NRC sponsored the update to the Data Collection Handbook (DCH) and "Default Parameter Values and Distribution in RESRAD-ONSITE V7.2, RESRAD-BUILD V3.5, and RESRAD- OFFSITE V4.0 Computer Codes." Appendix C to NUREG/CR-7267[8] provides data on the parameter distributions that are used in RERAD-ONSITE 7.2.

Although site-specific parameter distributions are always preferred, as a first step, K_d distributions specific to *soil type* from the DCH may be used to perform probabilistic sensitivity analysis to better understand the sensitivity of dose to K_d. While NUREG-1757, Volume 2, Rev. 2 (NRC 2022), provides new guidance on the use of laboratory experiments to derive K_ds, if found to be risk-significant, it does not require laboratory or even experimental support in all cases. Other methods, such as reviewing the literature to identify factors (e.g., geochemical parameters, soil type, groundwater quality/chemistry) most important to the distribution coefficient for the particular radionuclides of concern may be used to identify site-specific information that can be used to reduce the uncertainty in the parameter value. Examples are provided below.

3.3.2. How do you Determine if a Parameter Value is Risk-Significant?

If a set of radionuclides does not contribute more than 0.025 mSv/yr total effective dose equivalent to the average member of the critical group, considering uncertainty, then the set of radionuclides can be considered "insignificant" and detailed modeling of the set of radionuclides is unnecessary. However, the dose contributions from the set of "insignificant radionuclides" should be considered (e.g., if a set of radionuclides contributes less than 0.025 mSv/yr then the dose standard can be reduced to 0.225 mSv/yr for the other significant radionuclides and no additional detailed modeling to consider the dose contributions of the "insignificant radionuclides" is needed). Therefore, as a starting point, only K_d values for radionuclides that have a potential to lead to doses greater than 0.025 mSv/yr may require additional support, and only if they are found to be risk-significant. For example, if there is little uncertainty in the K_d value additional support is likely unneeded.

[8] Note that NUREG/CR-7267 (NRC 2020c) updates NUREG/CR-6697, "Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes" (Yu et al. 2000) and therefore, NUREG/CR-7267 provides the latest information on RESRAD Family of Codes parameter support.

The next step is to determine if the dose is sensitive to the K_d value. If a parameter is important to the compliance demonstration based on sensitivity analysis (e.g., sensitivity analysis conducted using a reasonable range of K_d values that is expected to be appropriate for the site reveals (i) that the dose limit could be approached or exceeded, or (ii) that the parameter is strongly correlated to dose), then additional justification would typically be necessary to support the deterministic value selected (i.e., an analyst should not simply apply the 25th or 75th percentile values and assume these values are demonstrably conservative without further support). Again, this does not mean laboratory experiments are required to support risk-significant parameters, but as a first step, it is suggested that the analyst provide an assessment of the pedigree of data used to develop the parameter distributions in the literature. For example, three potential issues with use of parameter distributions from the literature, (i) sparse data, (ii) low quality data, and (iii) overly broad distributions could lead to risk dilution or an underestimate of dose if used in the compliance demonstration. Examples are provided on how use of the 25^{th} or 75^{th} percentile from the literature could lead to an underestimate of the dose. Some questions that should be asked include the following: (i) what is the range of values for the risk-significant parameter based on site-specific conditions for parameters important to K_d (e.g., pH, E_h), and (ii) how much data is available to support selection of a site-specific or even a partially site-specific value based on soil type or geochemical parameters?

It may be obvious that if data available to develop a parameter distribution are sparse or of low quality (e.g., see examples in NUREG-1757, Volume 2, Appendix I, regarding poorly designed or interpreted experiments), then the distribution may not reflect site-specific conditions. However, it may be more difficult to understand the impact of overly broad distributions on the compliance demonstration. For certain radionuclides, it is not atypical for K_d to range several orders of magnitude given variability in the value based on several factors such as pH, oxidation-reduction potential, and the presence of competing ions that can vary significantly across different sites. If an analyst were to select the 25th or 75th percentile of the broad distribution that covers all types of sites for the deterministic value to support the compliance demonstration, it is possible that a representative K_d for a particular site could fall at more extreme percentiles (less than 25^{th} percentile or greater than 75^{th} percentile) of the overall distribution. If an analyst is relying on a probabilistic compliance demonstration, then use of an overly broad distribution could also lead to risk dilution and an underestimate of the peak of the mean dose. NUREG-1757, Volume 2, Rev. 2, Appendix Q (NRC 2022), further discusses issues with sparse data, representativeness of data, and risk dilution, and provides examples of each.

In some cases, it may be necessary to provide additional support for the K_d values selected, typically when the compliance decision is sensitive to the K_d parameter value selected. Reduction in the uncertainty of the parameter value may lead to cost savings by averting more costly remediation to demonstrate compliance with the release criteria. In these cases, various approaches are available to provide additional parameter support (see list below). For especially risk-significant parameter values (e.g., those parameter values where uncertainty in the parameter value leads to uncertainty in the compliance demonstration), multiple lines of evidence or stronger methods (i.e., experimental methods) may be needed. A graded approach should be used in determining the need for additional parameter support.

ASTM C-1733 is one acceptable method that can be used to obtain experimental support for K_d (other types of experimental approaches such as column experiments in addition to the batch method are also available). Other non-experimental methods are also available as described in NUREG-1757, Volume 2, Rev. 2, such as matched pore water/soil samples, calculated values from tracer testing or contaminant plume information. Another approach is the use of lookup tables with site-specific data on important parameters such as pH and cation exchange capacity

(CEC). Geochemical or surface complex modeling using site-specific information is also an option in addition to review of the literature using site-specific information including soil type and geochemical conditions. Methods to provide support for K_d values include the following:

a) lookup tables (e.g., regression equations based on fit of key K_d parameters to experimental data available in the literature),
b) laboratory batch,
c) in situ batch method (i.e., matched pore water, solids field or laboratory analysis),
d) laboratory flow through (or column) method,
e) field modeling method, (e.g., migration rate observations),
f) K_{oc} method (empirical equations using organic carbon percent), and
g) geochemical modeling.

3.3.3. Examples of Limitations of Literature Values

The following section is intended to provide illustrative examples of potential issues associated with use of literature values for K_d, as well as provide examples of how site-specific distributions can be developed. Please note that the example data should not be used by licensees, because the data used to demonstrate the points does not necessarily represent the latest information available in the literature, but rather is used for illustrative purposes only.

3.3.3.1 Examples Showing the Impact of Geochemistry on K_d

Many factors can influence the selection of distribution coefficients (or K_ds) most notably the geochemical conditions at a site. Therefore, default K_ds or parameter distributions, found in literature, can vary greatly from site-specific K_d values that are derived based on field or laboratory experiments. As discussed above, K_ds based on literature values derived from limited, sparse, or low quality (non-representative) data can vary significantly compared to K_d values based on site-specific information. In other cases, the K_d may be based on many sites, but the distributions are so broad that the values used for any particular site may fall on the very high or very low end of the distribution that represents all types of sites. Therefore, care should be taken when selecting the K_d for a particular site to ensure that the values selected do not underestimate the dose. Multiple lines of evidence may be used to support K_d values if found to be especially risk-significant.

For example, the literature values for Americium (Am-241) can be found in Yu et al. (2015). For the generic soil type category (i.e., includes data for all soil types), Table 2.13.5 of the handbook reports a value of 7.86 for the underlying mean and a value of 1.79 for the underlying standard deviation of the normal distribution. NUREG-1757, Volume 2, Rev. 1 (NRC 2006a), included guidance that indicated that the 25th or 75th percentile of the parameter distribution, whichever was more conservative, could be used as the default value for the K_d based on the sensitivity results (e.g., if the lower K_d was more conservative given the importance of groundwater dependent pathways to dose, then the 25th percentile of the dose distribution could be used). NUREG-1757, Volume 2, Rev. 2, removed the earlier guidance found in Rev. 1 and replaced it with guidance indicating that additional site-specific support may be needed to support risk-significant parameters (or parameter distributions) such as K_d. For the purposes of this example, the 25th (or 75th) percentile value can be calculated, using the following equation:

$$K_{d,\,25th} = \mu + z_{25th} * \sigma$$

$$K_{d,\,75th} = \mu + z_{75th} * \sigma$$

The z-score for the 25th (and 75th) percentiles are -0.675 and +0.675, respectively. Using the equation above, the 25th percentile of the underlying normal distribution is 6.65 and the K_d value is $e^{6.65}$ or 770 cm^3/g.

However, as shown in the next several paragraphs, Am-241 is strongly pH dependent, and the literature values can vary significantly. Figure 3.9 is taken from the EPA report, "Understanding Variation in Partition Coefficient K_d Values Volume III" (pg. 5.6)(EPA 2004). The solid line connects the maximum K_d value reported at pH values of 4, 6, and 10 by Sanchez et al. (1982) with data represented with triangles. However, the Routson et al., values are orders of magnitude less than the Sanchez et al., values for similar pH (see black squares in Figure 3.9).

Given the assumed strong relationship of K_d to pH, measurements of pH at the site were considered in developing K_d using only the Sanchez et al. data set and based on an average pH value of 8 for measurements taken at the site. Assuming that pH is the only site data available to select K_d, a value of 55,000 cm^3/g was selected based on sensitivity analysis that showed that lower K_ds are more conservative and given the lowest value from Sanchez et al. for pH=8 is 55,000 cm^3/g. However, there is variability in the pH across the site and the representativeness of the pH measurements is also uncertain.

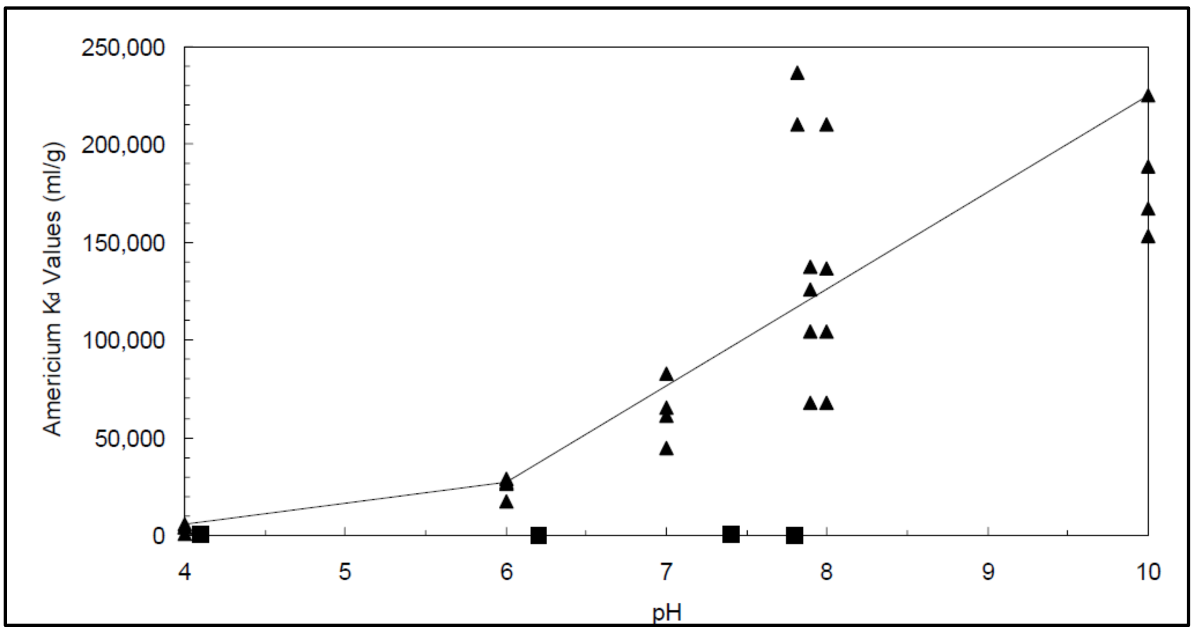

Figure 3.9 Americium K_d Values for Various pH.
Image credit: Sanchez *et al.* (1982).

To account for uncertainty in the pH measurements and associated K_ds, the EPA report (2004) indicates that partition coefficients measured at site-specific conditions are essential due to the sparsity of data. Additionally, a screening value of 4 cm^3/g at a pH range of 4 to 10 was recommended in the absence of site-specific information.

After initial scoping simulations that showed the doses could be over the release limits using the screening value of 4 cm^3/g, to reduce uncertainty in the K_d, site-specific data are collected, and a K_d value of 10 cm^3/g is calculated. Note that this site-specific data is hypothetical and created for the purposes of this example, but the hypothetical value falls within the range of the literature values for site-specific conditions (for pH of 8)[9] and is therefore considered plausible.

Deterministic K_d values of 4 cm^3/g (screening value recommended for pH between 4 and 10), 10 cm^3/g (hypothetical site-specific value based on K_d measurements with similar soil and pH), 770 cm^3/g (generic soil literature value from the DCH); and 55,000 cm^3/g (value selected based on site-specific information for pH and just the Sanchez et al. (1982) data) are used to determine the dose per unit concentration, as shown in Figure 3.10. These curves were generated in RESRAD-ONSITE by changing the K_d value of the source or contaminated zone, unsaturated zone, and saturated zone (note, that in reality, the K_d values for the three zones may differ although the K_ds are oftentimes correlated), while all other parameters were left to their default values.[10]

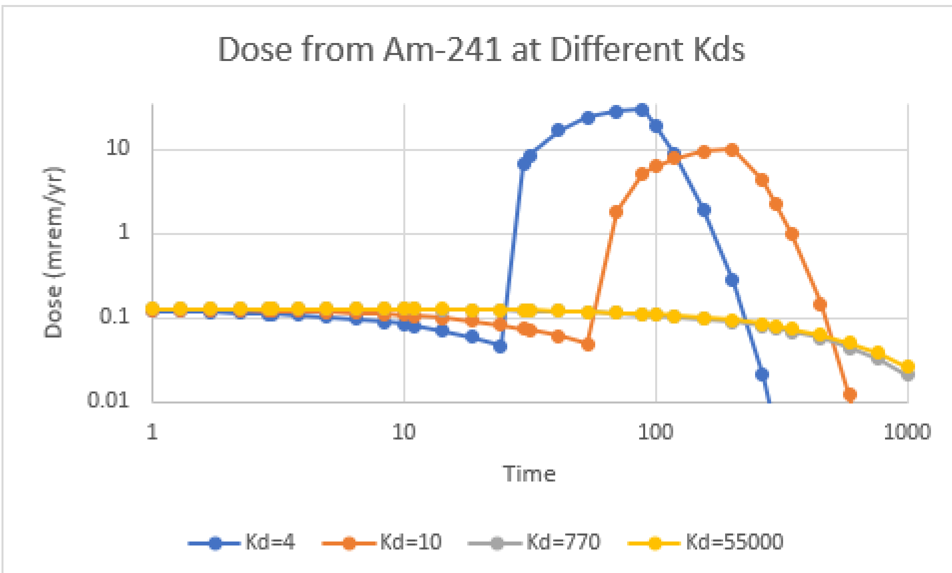

Figure 3.10 Am-241 Dose for Different Values of K_d Using all RESRAD-ONSITE Default Values for other Parameters. Note: 1 mrem/yr = 0.01 mSv/yr.

[9] Routson et al. (1975 and 1977) show that at a pH of 7.8 the lowest Am-241 K_d is 4 cm^3/g for experiments conducted with very to moderately dilute calcium and sodium electrolyte solutions with other values ranging from 6 to 1200 cm^3/g.

[10] Note that NUREG-1757, Volume 2, Rev. 2, indicates that the deterministic parameter values in RESRAD-ONSITE are not acceptable for use without additional justification. However, for the purposes of this example, the RESRAD-ONSITE defaults were all left as is for ease of calculation, because changes to the default parameter values were not considered important to demonstrating the influence of K_d on peak dose.

Table 3.3 K_d and Peak Dose from Am-241 for Various K_ds

Case	K_d (cm^3/g)	Peak Dose (mSv/yr)
Screening Value (pH between 4-10)	4	0.30 (@ 89 years)
Site-Specific (hypothetical but loosely based on Routson et al., data)	10	0.10 (@ 203 years)
Literature Value (all soils, no consideration of chemistry)	770	0.0013 (@ 0 years)
Partial Site-Specific/ Literature Value (based on pH 8 and Sanchez et al, data)	55,000	0.0013 (@ 0 years)

As shown in Table 3.3, the overall dose peak and time of peak dose varies significantly based on the K_d value selected (from 1.3 to 300 µSv/yr). As illustrated in Figure 3.10, the highest peak doses are associated with lower K_ds. The timing of the peak dose also occurs earlier in the case of a K_d =4 cm^3/g versus K_d =10 cm^3/g. While the timing of peak dose may not be considered important, given the fact that Am-241 has a 432-year half-life, enhanced transport rates could lead to significantly less decay and higher peak dose. The peak dose for higher values of K_d from the literature (25th percentile value from the RESRAD-ONSITE default parameter distribution for all soils of 770 cm^3/g and literature value based on site-specific pH of 55,000 cm^3/g) occur at time=0 years owing to the importance of surface dose pathways rather than groundwater dependent pathways when the K_d reaches a certain value above which transport of the radionuclide to the underlying groundwater aquifer does not occur within the simulation period. However, because groundwater dependent pathways dominate the dose compared to non-groundwater dependent pathways, if the radioactivity is able to reach the groundwater aquifer, lower K_ds result in significantly higher peak doses although the peak dose occurs later in time following leaching and transport of the radionuclide to the water table aquifer. This example shows that use of generic literature values can lead to less conservative results compared to site-specific values. Additionally, multiple factors may influence the K_d, leading to a situation where use of site-specific geochemical information for one parameter may still lead to an under-prediction of dose if another factor is also important to K_d but is not well understood or cannot be discerned based on the data available in the literature (e.g., K_d values for pH around 8 are drastically different for the data sets collected by Sanchez et al. (1982), versus Routson et al., suggesting that other geochemical parameters are also important to K_d or that one of the data sets is not representative or based on flawed experimental data).

Using literature data on K_d based on soil type may also lead to an underestimation of dose. For example, if a site has sandy or clayey soil, licensees may use literature values for K_d that apply to sand or clay soils thinking that is always sufficient to support site-specific K_ds. However, depending on the radionuclide, geochemical properties such as oxidation-reduction potential or E_h, hydrogen ion concentration or pH, presence of competing ions, and other factors could also significantly affect the K_d value. Therefore, for some radionuclides, using literature data that broadly applies to one type of soil can oversimplify the problem and not reflect differences in geochemical parameters that may have a strong influence on K_d.

In the next example, site-specific data for plutonium (Pu) K_d from the Savannah River Site (SRS) in Aiken, SC, are presented. It is important to note that Pu can exist in multiple oxidation states, namely +3, +4, +5, and +6, with higher oxidation states typically leading to lower K_d

values. Literature values for Pu can also be found in Yu et al. (2015). In table 2.13.5, the mean and standard deviation of the underlying normal distribution are 6.61 and 1.39, respectively. This results in a 25th percentile of 5.67 and a K_d value of 290 cm^3/g.

This example illustrates the importance of considering site-specific information, such as E_h and pH and expected oxidation states of key radionuclides, in addition to soil type. Based on the CNWRA report entitled, “Recommended Site-Specific Sorption Coefficients for Reviewing Non-High-Level Waste Determinations at the Savannah River Site and Idaho National Laboratory,” the recommended SRS K_d value for Pu(III/IV) for subsurface sandy soil is 350 ml/g (pg. 2-63) and the recommended SRS K_d value for Pu(V/VI) is 9 ml/g (2-63), as reproduced in Table 3.4 (Prikryl and Pickett 2007). Additionally, the same oxidation state, Pu(V/VI), for subsurface sandy soil and subsurface clayey soil are compared in Table 3.4. Pu(V/VI) for subsurface clayey soil has a recommended K_d value of 50 mL/g (2-65).

The SRS recommended K_d values are based on site-specific data (e.g., laboratory and field experiments conducted using SRS subsurface materials and actual or synthetic groundwater to match the geochemical conditions at the site). The K_d values listed in Table 3.4 were used in the RESRAD-ONSITE computer code for the source or contaminated zone, unsaturated zone, and saturated zone K_ds. Additionally, a cover thickness of 1 m[11] and an erosion rate of 0 m/yr were also used as inputs to the code, while all other parameters were left at their default deterministic values. The dose per unit concentration output from RESRAD-ONSITE is also listed in Table 3.4.

Table 3.4 K_d Values from the Literature and for Various Oxidation States and Soil Types at Specific Sites

25th Percentile from Literature	SRS Subsurface Sandy Soil with Pu(III/IV)	SRS Subsurface Sandy Soil with Pu(V/VI)	SRS Subsurface Clayey Soil with Pu(V/VI)
K_d (cm^3/g)			
290	350	9	50
Dose Results (µSv/yr)			
7.3E-06 @1000 years	7.1E-06 @1000 years	200 @196 years	34 @1000 years

In this specific example, the difference in dose per unit concentration differs significantly depending on the assumed oxidation state of Pu, as well as the soil type (see Figure 3.11). This example further demonstrates the importance of understanding geochemical conditions at a site to adequately model the release and transport of certain radionuclides in the environment. Dissolved oxygen concentrations, mineralogy, E_h, pH, and other geochemical parameters can have a very significant impact on the oxidation state and K_d value of certain radionuclides of concern. When a specific soil type is assumed, the K_d values can also differ significantly, and lead to significant differences in the overall dose per unit concentration. Therefore, it is important to adequately understand all the important factors influencing K_d to accurately represent the release and transport of radionuclides at any particular site. In this case, if only the oxidation state or only the soil type is known, the dose per unit concentration may be significantly underestimated. Therefore, it is important to consider multiple site-specific

[11] In this case, a cover thickness of 1 m is used to focus attention on the groundwater dependent pathways. By providing a clean cover, surface dose pathways are not important and only the impact of K_d on leaching and transport is studied.

geochemical properties and how they may influence the transport behavior of radionuclides of concern. In actuality, the transport of redox sensitive radionuclides such as Pu is likely more complex then described in these examples with redox cycling occurring over time due to seasonal fluctuations in precipitation rates and other factors. Oxidation-reduction potential may therefore be spatially and temporally variant, adding complexity to the problem. NUREG-1757, Volume 2, Rev. 2, Appendix I, provides additional details on modeling complex systems, as well as discussing challenges associated with K_d averaging when multiple oxidation states are operable.

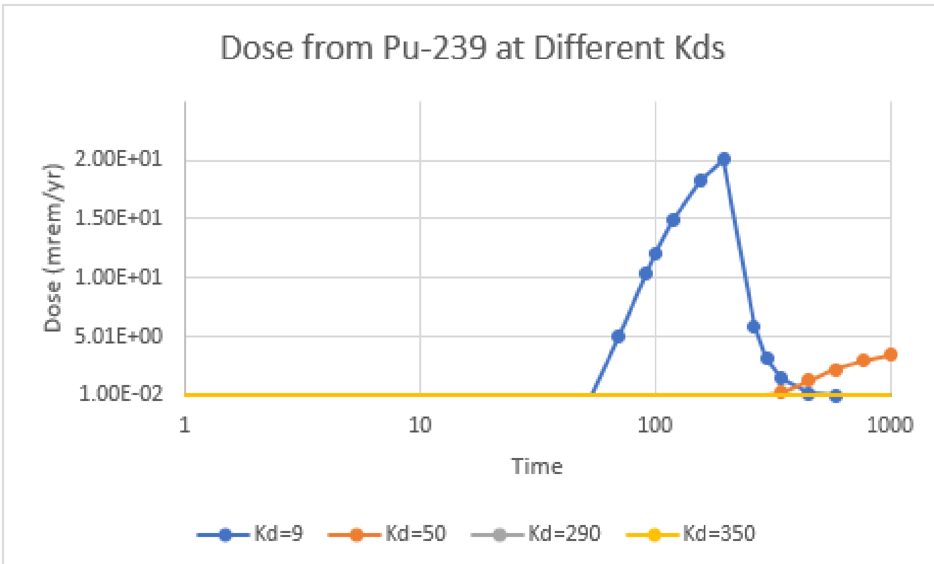

Figure 3.11 Peak Dose from Pu-239 Based on K_d. Note that the values for K_d =290 and K_d =350 cm³/g are around 1E-06 µSv/yr @1000 years. 1 mrem/yr = 10 µSv/yr.

3.3.4. Obtaining Support for Site-Specific K_d s

3.3.4.1 Sediment Textural (Soil Type) Information Considerations

Sediment texture or soil type is an important consideration in defining the conceptual model for the site and selecting an appropriate distribution coefficient or K_d. Before discussing challenges associated with sediment texture classification, it is important to discuss what exactly is considered soil. MARSSIM defines soil as the top layer of the earth's surface, consisting of rock and mineral particles mixed with organic matter. However, gravel or rock is typically removed from samples prior to analysis. 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. Typically analyzed soil samples consist of mineral and naturally occurring organic material that are 0.8 in (2 mm) 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 0.8-in (2-mm) size is generally compatible with analytical laboratory methods, capabilities, and requirements (EPA 1990). Figure 3-12 presents the particle sizing for soil; beyond the 0.8-in (2-mm) size, it is considered gravel, not soil. Additionally, in most situations, the vegetative cover is not considered part of the surface soil sample and is removed in the field. 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). It is important to note that discrete radioactive particles and discrete sources are not within the scope of this guidance, and the generalizations listed above about the characteristics of soils are not applicable to survey of discrete radioactive particles.

Figure 3.12. Soil Particle Sizing Chart. Image Credit: EPA 2000.

As a starting point for selection of K_d, it may be appropriate to consider site-specific information on textural classification of unconsolidated sediments (or what is more commonly referred to as *soil type*) to help constrain the K_d. Compilations of K_d values, such as those in the DCH (2015), provide tables for sand, loam, clay, and organic soils. There are two considerations when applying the textural classification approach for estimating K_d values. The first consideration is that many decommissioning sites have described their site's unconsolidated sediments using the Unified Soil Classification System (USCS) or the United States Department of Agriculture Textural Soil Classification (USDA TSC). Neither of these systems maps cleanly to the categories used in the compilations of K_d values. The second consideration is situations where a subset of the sediments at the site is selected for the contaminated zone, unsaturated zone, or saturated zone. For either consideration, the basis for the selection of K_d values and parameter distribution should be provided, which may include an explanation of how that selection does not lead to an underestimate of dose.

With respect to the first consideration, the earliest compilation by Sheppard and Thibault (1990) used the categories of sand, loam, clay, and organic soils. Since that time, other compilations expanded the database of supporting values, but retained the same textural categories. The DCH (2015) retains the categories for sand, loam, and clay, organic soil types, and includes a table for generic soil types. Sheppard and Thibault (1990) separated the sediment types as follows:

- Sand category defined as >70 percent sand-sized particles.
- Loam category has an even distribution of sand, silt, clay, and up to 80 percent silt.
- Clay category defined as containing >= 35 percent clay.
- Organic category defined as >30 percent organic material (e.g., peat).

The percentages are calculated by weight. Sand and loam are the most common categories for decommissioning sites; organic layers are generally near the surface but are often removed during construction; sites where clay is the only sediment are unusual.

Many sites use the USCS for borehole logs since the subsurface site characterization that exist prior to decommissioning is often driven by geotechnical needs. The USCS first separates unconsolidated sediments as coarse (sand and gravel) or fine (silt and clay) based on the majority weight percent that is retained or passed on a No. 200 sieve, which has 0.075 mm openings. Further subdivision of sand and gravel categories is done by degree of grading and percent fines. Grading is the amount of sorting, which is important in geotechnical analyses.

Well-graded sand contains fine, medium, and coarse grains of sand. Poorly graded indicates the presence of a narrow range of particle sizes or gaps in the distribution of particle sizes. As a side note, the USCS defines fines as particles passing through an opening of 0.075 mm, but other systems separate sands from silts somewhere between 0.002 to 0.075 mm particle size.

In the USCS,

- Coarse grained soil: >50% retained on No. 200 sieve (0.075 mm opening)
  - Gravels if >50% retained on No. 4 sieve (4.75 mm opening)
    - GW, GP, GM, GC separated by grading and percent fines
    - Lower end of very fine sands, note silt generally 0.002 to 0.05 mm
  - Sand if >50 percent passes through a No. 4 sieve (4.75 mm opening)
    - SW is well-graded with little or no fines (<5 percent)
    - SP is poorly graded sand with little or no fines (<5 percent)
    - SM is silty sands >12 percent fines
    - SC is clayey sand >12 percent fines
- Fine grained soil: >50% or more passes No. 200 sieve (0.075 mm opening)
  - ML, CL, OL when liquid limit[12] is <50 percent for silt, lean clay, or organic

SP and SW soils using the USCS fit directly into the K_d category of sand based on percent fines (silt, clay). However, SM soils could map into the K_d category of either sand, loam, or clay.

A second system used by soil scientists is the morphological-based system such as the USDA TSC that is qualitatively tied to a wide range of intrinsic properties. This system includes the sand-silt-clay triangle separated by component weight percentages into 12 or more areas of the triangle with names such as sand, silt loam, fine clay loam, and loam (see Figure 3.13). A sand and a loamy sand would both map to the K_d database category of sand, but a sandy loam or sandy clay loam could map to either the K_d category of sand or loam depending on the weight percentage of silt and of clay.

Therefore, when site characterization utilizes either the USCS or the USDA TSC, additional information beyond textural name for unconsolidated sediments may be required to select the appropriate K_d database category of sand or loam. Justification for the selection should be provided that is consistent with the K_d database constraints on the sediment textural information. If the additional information is not available or will not be collected, an approach should be used that tends to over- rather than underestimate the concentrations and dose, which will be dependent on the exposure scenario and dominant pathways.

Another consideration for assignment of K_ds is related to the selection of the subset of the sediments at the site for the contaminated zone, unsaturated zone, and saturated zone. There are often a variety of sediment types at a site, such as sites overlying sediments derived from fluvial environments with interlayered clays, silts, and sands. In addition, backfill around structures and fill for leveling the site may be used during facility construction or for later use. If a subset of the unconsolidated sediments at the site are used as a basis for setting K_d distributions or values, technical justification should be provided that considers the expected transport pathways and materials encountered along those pathways. For example, if K_d values for loam are assigned to the contaminated zone[13] at a site with a variety of sediment textural types, a basis should be provided for why source areas of the subsurface at the site are limited

[12] Liquid limit can be treated as moisture content for the purposes of the discussion in this section of the ISG.

[13] The contaminated zone in RESRAD-ONSITE represents the source zone, where leaching occurs.

to loams. As described in the above paragraphs, the soil texture criteria relevant to the K_d compilations should be used.

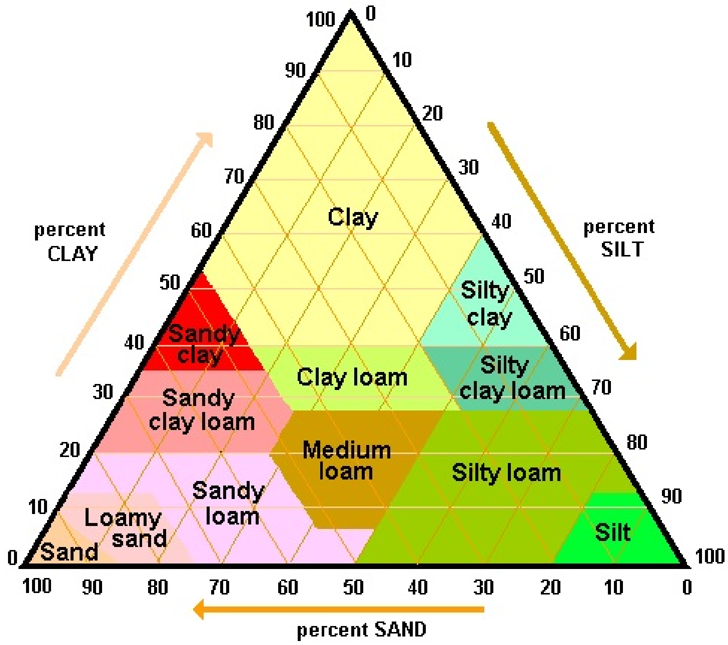

Figure 3.13 USDA soil texture classification chart.

3.3.4.2 Developing Site-Specific K_d Values Using Regression Equations

Regression equations of sufficient quality may also be available to determine radionuclide K_d at some sites. These regression equations, often found in literature, can be another technique used to estimate the K_d value of a specific site. Lookup tables are provided for certain radionuclides in the EPA report, "Understanding Variation in Partition Coefficient K_d Values" (EPA 1999). These lookup tables have linear regression models from experimental data to determine K_d value. For example, a regression model is provided for cesium in the report. Figure 3.14 shows two regression models: (i) CEC vs clay content, and (ii) CEC vs K_d value. Using these two regression models, a K_d value can be determined if the clay content of the soil is known.

As an example, suppose the clay content percentage of the site is known to be 20 percent. Using the linear regression equation, with x equal to 20, the CEC yields 12.9. Therefore, a log (CEC = 12.9) equals 1.11. Using the second regression equation, with x =equals 1.11, the log (K_d) equals 2.9. Therefore, the site-specific K_d value is calculated as 795 cm^3/g. This method may be useful in providing additional benchmark checks when limited data are available in the literature. For example, looking at Yu et al. (2015), the literature value for clay soil of cesium has only 36 samples. The literature K_d distribution, using the 25th percentile, parameter results in a K_d value of 987 cm^3/g. Therefore, using regression models can help provide additional support and confidence for literature values if the K_d values result in similar values.

It should be noted that depending on the radionuclide, some variables correlate better than others. For example, the R^2 value for the cesium data in Figure 3.14 is 0.63 and 0.60. Typically, R^2 values closer to 1 are seen as having a stronger correlation between the x and y axis variables. As shown in Figure 3.15, radionuclides, such as strontium, have linear regression equations with R^2 values closer to 0.7 and 0.8. Therefore, the statistical indicators, such as R^2, should also be considered when determining a K_d value.

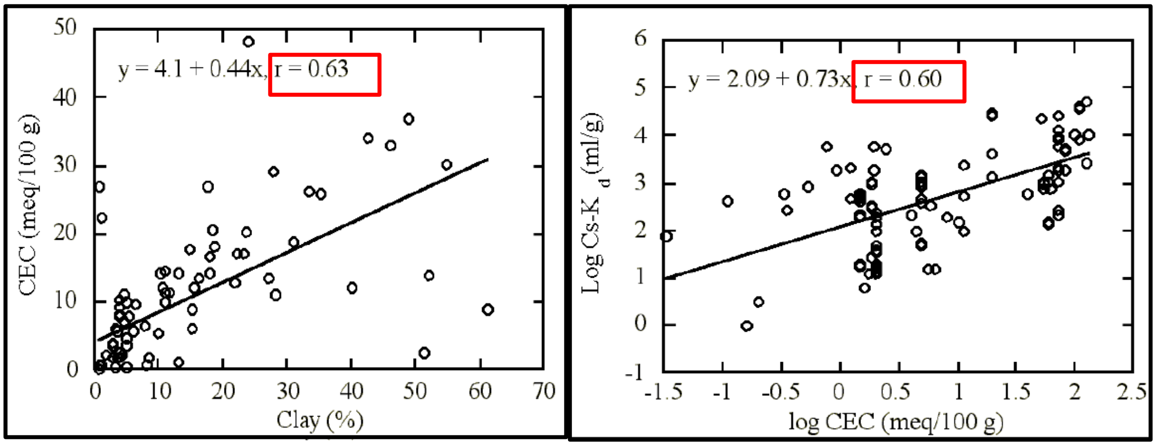

Figure 3.14 CEC Versus Clay Content and Cs K_d Value Versus CEC. Image Credit: Figure D.1 and D.2, "Understanding Variation in Partition Coefficient Kd Values Volume II: Review of Geochemistry and Available Kd Values for Cadmium, Cesium, Chromium, Lead, Plutonium, Radon, Strontium, Thorium, Tritium (3H), and Uranium" (EPA 1999).

#	Equation	n[2]	Data Range [3]	95% Confidence Limits[1]						R^{2} [4]	F Value[5]
				Intercept		Slope First Independent Parameter		Slope Second Independent Parameter			
				Lower	Upper	Lower	Upper	Lower	Upper		
1	K_d = -272 + 126(CEC)	63	All	-501	-43	105	147	---	---	0.70	1×10^{-17}
2	K_d = 114(CEC)	63	All	---	---	95	134	---	---	0.67	2×10^{-16}
3	K_d = 10.0 + 4.05(CEC)	57	CEC<15	3.32	16.6	2.13	5.96	---	---	0.25	9×10^{-5}
4	K_d = 5.85(CEC)	57	CEC<15	---	---	4.25	7.44	---	---	0.12	7×10^{-3}
5	K_d = -42 +14(CEC) + 2.33(pH)	27	All	-176	91	11.3	18.3	-17.7	22.4	0.77	3×10^{-8}

Figure 3.15 Lookup Table Values for Sr K_d with Goodness of Fit Measures. Adapted From: Table H.3, "Understanding Variation in Partition Coefficient Kd Values Volume II: Review of Geochemistry and Available Kd Values for Cadmium, Cesium, Chromium, Lead, Plutonium, Radon, Strontium, Thorium, Tritium (3H), and Uranium" (EPA 1999).

3.4 Exposure Scenarios for Subsurface Residual Radioactivity

As discussed above, intrusion scenarios, which could bring residual radioactivity to the surface, should be considered in developing $DCGL_V$ for subsurface materials that would otherwise be less accessible to members of the public. Exposure scenarios for the subsurface include leaching of residual radioactivity to groundwater and various scenarios in which the subsurface is disturbed and brought to the surface (e.g., well drilling, home construction, large construction project). NUREG-1757, Volume 2, Rev. 2, Appendix J (NRC 2022), provides examples for exposure scenarios that should be considered for buried or subsurface residual radioactivity. This does not mean that all intrusion scenarios must be analyzed; however, the likelihood of a range of potential intrusion scenarios should be assessed and arguments presented for inclusion or exclusion of the intrusion scenarios from detailed analysis. Typically, one or more intrusion scenarios and the “as is” leaching to groundwater scenario are evaluated.

Alternatively, an analysis can be performed that assumes that the surface soil above the top of the buried residual radioactivity is absent (see Figure 3.16b). 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 so as not to prolong the travel time to groundwater. 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.

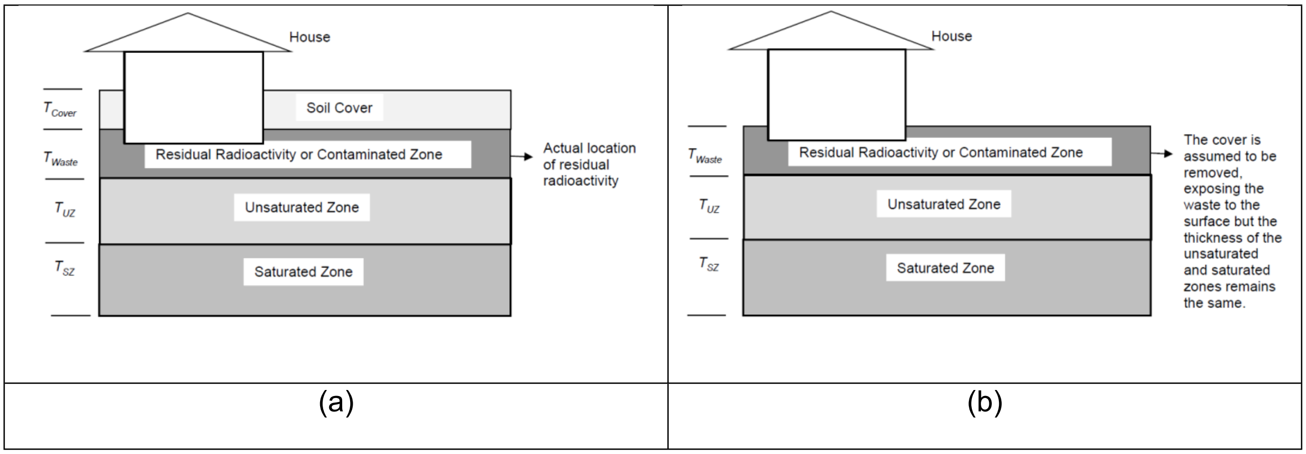

Figure 3.16 Simplified Conceptual Model of Human Disturbance into Buried Residual Radioactivity (The Left Panel Shows the Original Configuration of Residual Radioactivity and Human Disturbance Event [Construction of a Home with Basement]; the Right Panel Shows a Conceptual Model with the Cover Assumed to have been Removed for Simplification). Image Credit: Figure J. 3 in NUREG-1757, Volume 2, Rev. 2 (NRC 2022).

3.5 DCGL Development

This section discusses the need for and considerations with respect to development of $DCGL_{EMC}$ for smaller areas of elevated activity. Because licensees have the option to develop multiple DCGLs for surface and subsurface residual radioactivity, information is also provided on how multiple DCGLs can be considered in the compliance demonstration.

3.5.1. $DCGL_{EMC}$

The need for $DCGL_{EMC}$ values is based on site-specific considerations including the likelihood of potential exposure of members of the public to small volumes of residual radioactivity in the subsurface (e.g., well driller scenario). Arguments can be presented for why exposure scenarios in NUREG-1757, Volume 2, Rev. 2, Appendix J (NRC 2022), do not need to be considered using the “likelihood” framework provided in Chapter 5 (e.g., exposure scenarios in Table 3.1 are binned into groups based on likelihood including reasonably foreseeable, less likely but plausible, and implausible exposure scenarios). Implausible exposure scenarios do not need to be considered; and less likely but plausible exposure scenarios do not need to be considered for compliance but are considered simply to risk-inform the decision. In some cases, licensees calculate a single, effective $DCGL_W$ for each ROC considering in situ leaching, well drilling, and excavation scenarios. In lieu of a $DCGL_{EMC}$, each measurement can be compared to the effective $DCGL_W$. Use of a single $DCGL_W$ can be a simple and effective method for demonstrating compliance with release criteria.

The importance of elevated areas in the subsurface differs significantly from elevated areas in the surface due to the relative inaccessibility of subsurface materials. In most cases, a member of the public can only be exposed to small volumes of subsurface materials in the subsurface from human activities that may bring residual radioactivity to the surface as described in NUREG-1757, Volume 2, Rev. 2, Appendix J (NRC 2022). For example, a well driller scenario may be an appropriate scenario to be considered in developing $DCGL_{EMC}$, but due to the low risk of bringing a small volume of subsurface materials to the surface compared to other potential exposure scenarios, a licensee may choose to sum the well driller dose with the dose from larger-scale excavations using an effective $DCGL_W$ approach to demonstrate compliance eliminating the need to develop separate $DCGL_{EMCs}$. Every site is different, and licensees should consider the costs and benefits of various approaches in determining the need for development of $DCGL_{EMCs}$. Licensees are encouraged to contact NRC staff early in the process to discuss various options for development of DCGLs. For licensees that elect to develop $DCGL_{EMCs}$, future NRC plans are to develop a methodology and associated tools that will support remedial and FSS decision-making using a multi-scale approach (i.e., considering various volumes of residual radioactivity with different action levels) as described in Section 1.2.

3.5.2. Multiple DCGLs

Because dominant pathways for subsurface versus surface residual radioactivity may differ, licensees may develop multiple DCGLs to account for differences in risk-significance. For example, external dose and inhalation pathways tend to dominate the dose from surface soils; the plant ingestion pathway may be important for intermediate depths; and the groundwater pathway may dominate dose from residual radioactivity deeper in the vadose zone. Intrusion scenarios should also be considered when developing subsurface DCGLs, which could lead to surface (rather than subsurface) dose pathways dominating the dose for certain radionuclides after residual radioactivity at depth is assumed to be redistributed to the surface.

In cases where different sets of DCGLs are developed for different strata, it is important to ensure that the average contaminant concentration in each stratum is lower than the applicable DCGL for that stratum and the cumulative dose from all strata are assessed using a sum of fractions approach. Elevated areas should also be appropriately investigated and addressed, if found to be important to the compliance demonstration. When multiple DCGLs are present, an adaption of the unity rule described in NUREG-1757, Volume 2, Rev. 2, Section G.3.2 (NRC 2022), can be used to demonstrate compliance with release criteria. This is akin to use of Equation 8-2 in MARSSIM, Rev. 1, for multiple contaminated media or strata in addition to multiple radionuclides or elevated areas. Licensees may also choose to use a single (most conservative) DCGL to simplify the compliance demonstration. This approach is generally acceptable, provided the licensee doesn't use the single DCGL to justify dilution of higher activity surface concentrations with lower activity subsurface concentrations to meet the DCGL. The licensee should use sensitivity analysis to better understand the importance of source parameters (area, thickness and depth of residual radioactivity) on dose and take depth discrete measurements if necessary to demonstrate compliance. Additionally, the total thickness and depth of residual radioactivity would also need to be factored into the DCGL calculation.

4. SPECIAL CONSIDERATIONS FOR SITES WITH EXISTING GROUNDWATER CONTAMINATION

4.1 Consideration of Risk for Existing Groundwater Contamination

4.1.1. Calculation of Groundwater Dependent PDCFs

The DandD and the RESRAD-ONSITE conceptual models do not consider existing groundwater plumes located in the saturated zone when calculating dose or deriving screening values and DCGLs. In many cases, if there is existing groundwater contamination, licensees have apportioned a fraction of the dose limit to the groundwater pathway to demonstrate license termination rule criteria have been met (e.g., 5 mrem/yr (0.05 mSv/yr) of the 25 mrem/yr (0.25 mSv/yr) dose limit for unrestricted release). The RESRAD-ONSITE computer code has been used to calculate what is referred to as a pathway dose conversion factor (PDCF) for groundwater dependent pathways (e.g., drinking water, irrigation, livestock watering) in units of mrem/yr per pCi/L (or mSv/yr per Bq/L). The dose from existing groundwater contamination for all the potential uses of the groundwater are therefore considered. This section discusses how RESRAD-ONSITE can be used to calculate the pathway dose conversion factors for a unit concentration of groundwater. Section 4.2 discusses how data from the groundwater monitoring network can be used to estimate the potential dose using the PDCF.

While the RESRAD-ONSITE computer code does not consider doses associated with existing groundwater plumes, the computer code can be used to calculate groundwater pathway dose conversion factors by running the code with some source concentration in the subsurface[14] for an individual radionuclide and extracting the maximum[15] groundwater well concentration and associated peak dose from groundwater dependent pathways such as drinking water, irrigation, fish ingestion, and livestock watering. Table 4.1 below presents some example groundwater PDCF calculations using the default parameter values[16] in RESRAD-ONSITE. Please be aware that these values are provided for illustration purposes only, and only site-specific parameter values should be used in calculating PDCFs for actual sites. For some constituents, the assumed distribution coefficient used in the simulation may be so high that the constituent is unable to travel to the saturated zone from the contaminated zone within the timeframe of the simulation and no PDCF can be calculated. In these cases, if site-specific conditions lead to the presence of the constituent in the saturated groundwater, then the conceptual model for contaminant release and transport may need to be revisited to ensure it aligns with dose modeling assumptions (e.g., presence of the source in the saturated zone, differences in geochemical conditions that resulted in faster transport rates). Adjustments to the model/parameters may be needed to enable calculation of PDCFs for those constituents. For example, updated versions after RESRAD-ONSITE version 6.5 allow placement of the source directly in the saturated zone. Placing the source in the saturated zone will facilitate transfer of

[14] By running a source in the subsurface (i.e., with a clean cover) with minimal erosion (e.g., 0 m/yr erosion rate), the peak dose will automatically be associated with groundwater dependent pathways (no surface pathway dose will result which could complicate calculation of the groundwater dependent pathway dose). Alternatively, RESRAD-ONSITE Version 6.5 allow the analyst to place the source directly in the saturated zone, which will expedite transport to the well.

[15] Any matched groundwater dose and associated concentration can be used to calculate the groundwater pathway dose conversion factor, although the peak concentration may be preferred.

[16] Default parameter values except for the cover thickness and erosion rate

residual radioactivity to the well ensuring well concentrations will be realized to allow calculation of PDCFs.

It is important to note that while many of the site-specific (physical) parameters selected affect the ratio of concentration in groundwater per unit concentration in soil, they do not necessarily have an impact on the ratio of the dose per unit groundwater concentration. Only certain biosphere parameters influence the PDCFs (e.g., behavioral parameters such as drinking water intake, irrigation rates, and livestock water intake). It is always prudent to use the licensee's dose modeling files with their site-specific biosphere parameters already specified to calculate the pathway dose conversion factors. When performing these calculations, an analyst may need to adjust the graphics parameters, calculation times, or time integration points to get more accurate PDCFs.[17] Checks on the stability of PDCF over different times and with different source parameter specifications (e.g., distribution coefficients and thickness of contaminated zone) should be made to ensure that rapidly depleting sources early in the simulation period do not lead to inaccuracies in the PDCF calculation.

Table 4.1 Example PDCFs

Radionuclide	Maximum GW Concentration from Unit Concentration	Peak Dose from Groundwater Dependent Pathways	PDCF mrem/yr per pCi/L[a]	Benchmark PDCF mrem/yr per pCi/L[a]
H-3	1065 pCi/L	0.10 mrem/yr @4.3 years	9.4E-05	4.4E-05[b]
Tc-99	1357 pCi/L	2 mrem/yr @4 years	1.5E-03	1.2E-03[b] 5E-03[c]
C-14	1367pCi/L	6.7 mrem/yr @4.4 years	4.9E-03	1.3E-03[b] 0.014[c]
Sr-90	0.01 pCi/L	6.9E-04 @227 years	0.069	0.34[c]

Note: RESRAD-ONSITE defaults were used except for 1 m cover and 0 m/yr erosion rate.
[a] 1 mrem/yr = 0.01 mSv/yr; 1 pCi/L = 0.037 Bq/L
[b] SRS F-Tank Farm Performance Assessment Pathway Dose Conversion Factors excluding stream pathways.
[c] LaPlante, P.A. and K. Poor. 07/25/1997. "Information and Analyses to Support Selection of Critical Groups and Reference Biospheres for Yucca Mountain Exposure Scenarios." CNWRA 97-009. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1997. 20.05708.761, Q199709240001, ML040200056, Table E-1.

4.2 Methods to Estimate Magnitude and Extent

This section discusses methods to estimate the magnitude of existing groundwater contamination that is used as input together with the PDCF to estimate final dose due to existing groundwater contamination. The PDCF is discussed in Section 4.1.1. Existing groundwater contamination refers to residual radioactivity in the groundwater during the time leading up to the FSS. The maximum residual radioactivity in a groundwater plume should be used in the input to calculate existing groundwater dose. Several approaches are discussed for choosing concentration values for use in calculating dose for the set of radionuclides existing in the groundwater. The selection of an approach is graded, depending on the site complexity, magnitude and trends of existing radionuclide concentrations, and level of conservativeness found acceptable to the licensee. These approaches address a holistic perspective that

[17] Note that the RESRAD 6 User's Manual (ANL 2001) indicates that the instantaneous dose will be reported if the time integration parameter is changed to 1. Therefore, the dose will more closely match the instantaneous concentration at the selected time.

evaluates the utility of the distribution of monitoring wells in relation to likely or potential source areas. For areas where wells are not located and where groundwater contamination might be the highest at the site, the holistic perspective also recognizes that useful information may be obtained from the relationship between measured subsurface soil radioactivity and potential estimated pore water radioactivity. Before discussing possible approaches, the regulatory requirement for groundwater and several relevant concepts are discussed to help provide context for selecting the most appropriate approach(es) to apply at a site.

The dose criteria of 0.25 mSv (25 mrem) per year in 10 CFR 20.1402 for unrestricted release explicitly includes the contribution from groundwater sources. Generally, for practical reasons, the dose contribution for residual radioactivity in the groundwater is allotted as part of the LTP. The practical reasons are due to the inherent problems with performing a survey and/or sampling at the time of the FSS that could provide confidence that the maximum residual radioactivity is identified for the entire site and that it is decreasing prior to termination. With a dose allotted for existing groundwater contamination, the FSS analysis for termination should show that the groundwater residual radioactivity levels have remained below the values set in the LTP and are not increasing. It is presumed that groundwater remediation, if needed, has been completed and that ALARA principles have been followed.

Generally, licensees have been willing to apply the maximum groundwater contamination to the entire site for dose estimates for the FSS, hence there was no need to consider the lateral extent of groundwater contamination. However, there is no requirement that the maximum concentration be applied to the entire site, which would be a conservative approach. Determination of the extent of groundwater contamination, other than ensuring that no off-site release above relevant limits has occurred, is only needed for instances when the licensee chooses to apply different existing groundwater residual radioactivity levels to different areas of the site, or to different survey units. The level of effort needed to define variations of groundwater radionuclide concentrations across a site is greater than that needed to apply a uniform, maximum groundwater residual radioactivity concentration across the site. Some combination of an expanded monitoring well network that provides better coverage of the site and modeling of the extent of radionuclide contamination across the site would be needed to support the application of different levels of radionuclide concentrations across the site in the FSS. The level of effort may include more sampling locations, geospatial modeling, and more sophisticated groundwater flow and transport model; all of which may lead to different perspectives for NRC staff to review. Sites with a history of groundwater radionuclide contamination and remediation may have the additional wells and existing modeling needed to support estimating different maximum levels of residual radioactivity for different areas of the site in the FSS. An additional consideration is that not much may be gained by modeling the extent and distribution because groundwater radionuclide contamination is generally linked or correlated with the most soil-contaminated areas that are designated as Class 1 survey areas, and not in Class 2 and 3 areas where groundwater concentrations may be lower and where there is more leeway for conservative assumptions.

It is useful to consider the framework of detection, compliance, and performance monitoring networks as a site transitions from operations to decommissioning, and on to license termination. A component of the transition in site status should be an evaluation of the ability of the monitoring network design to address changes in objectives. During decommissioning, detection monitoring objectives take greater precedence, unless a groundwater remediation program needs to be initiated in which case performance monitoring objectives are implemented and may take precedence. If detection monitoring identifies a release, then characterization surveys to better understand the magnitude and extent of groundwater contamination should be initiated. Historically, however, sites may not have performed sufficient characterization to support remedial and compliance decision-making, as discussed in more detail in the next paragraph. While data collection may be driven by different objectives, the entirety of the data collected support FSS decision-making.

The maximum residual radioactivity in groundwater for a site likely does not occur at monitoring wells, although there are exceptions as mentioned below. Monitoring well networks may have information gaps that reduce the possibility of measured well data reflecting the maximum existing groundwater concentrations for the site, even if the network is consistent with the conceptual site model. Consistency of groundwater monitoring networks with the conceptual site model is discussed in NUREG-1757 Volume 2, Revision 2, Appendix F (NRC 2022). Wells may not be optimally located to measure peak radionuclide concentrations because (i) monitoring wells are often located at some distance downgradient of facilities or buildings, (ii) the well network may have been designed prior to a release or to identification of a source area, and (iii) source area may be within building footprints where wells are not typically placed. The information gap can be made worse during dismantlement when the wells closest to the potential source areas for groundwater contamination are also the wells most likely to be abandoned due to interference with deconstruction activities, which is a conundrum of monitoring network design for decommissioning. If relying on data from the well monitoring network and the source location is unknown, then the degree of underestimation of the maximum residual radioactivity in the groundwater is likewise unknown. The uncertainty of source locations is often relevant to historical leaks even if an event is identified in the HSA. For releases occurring during decommissioning, the source location may be more readily identified. Also, there are sites with groundwater contamination linked to known source areas where monitoring wells have been constructed adjacent to the source of the groundwater contamination either to help find the source, facilitate remediation, or monitor remediation progress. These wells located near an identified source may provide a sufficient estimate of maximum existing groundwater concentration. For other sites, alternative approaches should be utilized to address the information gap.

The concept of a transport length scale for each radionuclide needs to be considered. An assessment of the transport length scales for different radionuclides can be important for understanding the utility of the monitoring network, particularly for leaks occurring during decommissioning. For radionuclides leaked to the groundwater system, the time it takes for the radionuclide to migrate to the closest downstream well is a function of the site-specific sorption coefficient, the distance from the source to the monitoring well, the hydraulic gradient, and the effective porosity of the media. Ideally, the monitoring well network should be able to provide information about the magnitude and extent of the plume, as well as account for uncertainty in flow directions and rates. The frequency and length of monitoring should be a function of how rapidly contaminant concentrations are expected to change (e.g., more frequent monitoring for rapidly changing concentrations) and the timeframe over which risk-significant concentrations are expected to be observed.

4.2.1. Approaches

There are several approaches for estimating maximum existing groundwater contamination, including assessment of existing well monitoring, or leak/source data, subsurface soil radionuclide data with application of the sorption equilibrium relationship, direct sampling of the groundwater at locations of contaminated subsurface soil (i.e., potential source areas), modeling of groundwater flow and transport. A graded approach for selecting a method should be taken, whereby the level of effort is commensurate with the amount of uncertainty in the potential groundwater contamination and contribution to dose.

The first approach is assessment of monitoring well data for appropriateness in estimating the maximum groundwater radionuclide concentrations. Alternatively, maximum groundwater radionuclide concentrations could be estimated with information on leak events, such as mass flux released to the environment. If using well monitoring well data alone, a basis should be provided for the assumption that the well data reflects the peak concentration of the plume. This approach would be acceptable for situations where monitoring wells are in source areas where maximum plume concentrations are expected to occur. This is typically possible for sites where the source location had been identified, and remediation efforts may have been implemented. Additional wells may have been emplaced near the source at the time the historical release was identified. For the monitoring well data, assessment of trends and fluctuations would form a necessary basis for excluding the possibility of higher concentrations occurring between the time of the LTP and FSS and termination. Considering seasonal or other short-term variations in results, maximum residual radioactivity over a multi-year period should be used as input for dose calculation for existing contamination of groundwater contamination. The period of time is site dependent, and a basis should be provided that incorporates flow and transport characteristics and leak characteristics. The approach of using well monitoring data alone is discouraged for sites where the source location is unknown, and the existing monitoring network surrounds the facility at some distance. If the source location is unknown, or monitoring wells are located some significant distance downstream, then an additional approach for estimating the existing maximum concentration should be evaluated to supplement assessment of the monitoring well data.

The second approach, the equilibrium sorption approach, assumes that subsurface soil residual radioactivity found during characterization, continuing characterization, or dismantlement equilibrated with the groundwater. Remediation of soil ostensibly also removes groundwater equilibrated to that contaminated soil. So, the subsurface soil residual radioactivity to use for estimation of existing groundwater contamination is the contaminated soil below the remediated zone. An assessment of using soil DCGL values would provide a constraining value to use in the LTP. Besides the identified ROCs for existing groundwater, the entire suite of soil radionuclides should be evaluated using the equilibrium sorption approach in case there are insignificant contributors for soils that would be significant when considered for existing groundwater contamination. Assuming equilibrium sorption, the concentration found in soils (C_s) can be related to the concentration in the water phase (C_w) by

$$C_W = C_S * \rho_B / (\Phi * R_D)$$

where retardation (R_D) is defined as,

$$R_D = 1 + \rho_B * \frac{K_d}{\Phi}$$

which combined, leads to

$$C_W = C_S * \rho_B / (\Phi + \rho_B * K_D)$$

where ρ_B is bulk density, Φ is porosity, and K_D is sorption coefficient. This approach is valid for contaminated soils in the saturated zone but would be conservative for contaminated soils in the unsaturated zone due to dilution as the contaminants migrate and reach the saturated zone. The size of the contaminated area may affect the use of this approach. Justification for using average soil concentrations over small areas may be appropriate if a basis is provided. Selection of sorption coefficient values should be appropriate for the specific sediment in the contaminated zone. Consideration of the discussion on selection of site-specific K_d values in Chapter 5 of this guidance is needed to support the basis. This approach is most appropriate for radionuclides with lower values of sorption coefficients and higher dose conversion factors. Examples of elements with low K_d values are strontium, carbon, and cobalt, and maybe cesium depending on site characteristics. Sorption values of several hundred in units of L/cm^3 are unlikely to have significant concentrations in the groundwater near contaminated subsurface soil areas and can be screened out if PDCFs are also not large. In supporting the K_d values, possible geochemical characteristics of the leak solutions should be considered.

The third approach consists of direct sampling the groundwater at locations of suspected releases or subsurface soil areas with high measured values of residual radioactivity. Emplacement of temporary well points of any type can be used to obtain groundwater samples. If the contaminated subsurface soil is in the unsaturated zone, the most direct approach is to sample groundwater in the saturated zone below the contaminated area. Where the equilibrium sorption approach is considered too conservative for unsaturated or variably saturated (fluctuating water table), direct sampling of groundwater at the water table below the area could be used to reduce the uncertainty, complexity, and possibly the level of conservativeness.

In the last approach, groundwater flow and transport or geostatistical modeling can be used to estimate the maximum concentration in a plume. This approach is most useful if sufficient information on the leak concentration or location is known and there is sufficient hydrogeologic information to support a sophisticated model. NUREG-1757, Volume 2, Revision 2, Appendix F (NRC 2022) contains a discussion of model types and selection considerations.

Since the approach taken is site dependent, some justification or basis needs to be provided that addresses the available information from the site that may bear on maximum existing groundwater radionuclide levels.

4.2.2. DQOs for Existing Groundwater Contamination

DQOs should be developed for collection of data of sufficient quality to estimate groundwater exposure concentrations for use in dose modeling calculations. The general objectives and decisions associated with collection of groundwater data could include the following:

- **State the problem**—The problem for which data quality objectives need to be developed is assessing the dose to the average member of the critical group from existing groundwater contamination. This presumes a decommissioning site has significant residual radioactivity in groundwater such that detailed calculations or modeling are needed to assess the risk from existing groundwater concentrations or insufficient information is available to show that residual radioactivity in groundwater does not present a significant risk (see Section 3.3 of NUREG-1757, Volume 2, Rev. 2 (NRC 2022) for additional information on insignificant radionuclides and exposure pathways) due to potential exposure from groundwater dependent pathways.
- **Identify the Study Goal**—The goal of the study is to show that groundwater concentrations are less than DCGLs developed for existing groundwater contamination, or the dose from existing groundwater concentration is less than a certain dose (i.e., typically licensees apportion a fraction of the dose limit such as 3 mrem/yr (30 µSv/yr) for the groundwater pathway).

- **Identify Decision Inputs**—Groundwater exposure concentrations could be developed from analysis of groundwater monitoring data, or calculations and modeling used to determine appropriate concentrations to use in calculations to estimate the dose from existing groundwater contamination or for comparison against groundwater DCGLs. For example, if source areas are known, source area concentrations can be used to determine a conservative estimate of groundwater exposure concentrations near the source area. No matter which approach is taken, the list of ROCs that are pertinent to groundwater dose should be identified. Development of the list of ROCs should include (i) a basis for how the ROCs specific to groundwater media were selected, and (ii) a discussion on how insignificant ROCs are determined. The licensee should provide information on water quality parameters to be measured, minimum detectable concentrations, and laboratory analytical approaches in a monitoring plan or other document. Pathway dose conversion factors can also be calculated (see Section 4.1) to assess the dose per unit groundwater concentration to estimate the potential dose to the average member of the critical group.
- **Define Study Boundaries**—If monitoring well data will be used to determine exposure concentrations, the licensee should assess the adequacy of the monitoring well network for such purpose and the need for construction of additional monitoring wells or temporary piezometers to ensure the monitoring well coverage is sufficient such that groundwater pathway doses have a low likelihood of being under-estimated. If multiple source areas and radionuclides are present, the licensee should determine the adequacy of the monitoring well network to detect radioactivity in groundwater for each of the sources and radionuclides being measured. Additionally, the frequency and length of time groundwater will be monitored should be documented in a monitoring plan or other document.
- **Develop a Decision Rule**—If groundwater monitoring well data will be used to determine exposure concentrations, the licensee should consider how the data will be assessed and processed (e.g., review of historical data and site-dependent properties and evaluation of groundwater concentration trends). The licensee should determine if maximum groundwater concentrations from any source area (based on calculations or monitoring well data) will be estimated and the calculated dose added to the dose for each survey unit to assess cumulative dose from multiple contaminated media, or if more realistic modeling and assessment of groundwater flow and transport will be performed to estimate doses from the groundwater pathway. Approaches should be well documented, and a basis provided for the approach taken.
- **Specify Performance or Acceptance Criteria—**The licensee should describe the methods to be used to assess groundwater pathway dose—will a DCGL be developed for existing groundwater contamination based on a fraction of the release or dose limit and will groundwater monitoring well concentrations be compared to the DCGL (see Section 2.4), or will the dose from existing groundwater contamination be assessed using estimated exposure concentrations and PDCFs (see Section 4.1) and added to other media doses to demonstrate compliance with release criteria? The licensee should assess uncertainty in the methods used and any mitigative approaches to manage those uncertainties. QA/QC requirements should be specified in documentation for collection, processing, and laboratory analysis of collected data.
- **Optimize the Design**—A sampling and analysis plan or other documentation should be developed based on the monitoring plan or program, and data quality assessments

performed to ensure the quality of the data collected. Improvements to the monitoring approach can be made over time as additional data is collected and modeling is performed, as applicable.

As with other data for the FSS planning, information on uncertainty and minimum detectable concentrations for ROCs should be provided for groundwater samples. NUREG-1576 (NRC 2004) provides guidance on reporting laboratory results that should also be considered. For some sites, standard operating procedures may already cover uncertainty and detection sensitivity for groundwater samples. In general, objectives of monitoring should be well defined, and justification should be provided for decisions made as part of the DQO process.

4.3 Alternative Methods of Characterization for Locations of Known Leaks

At the May 11, 2022, subsurface workshop, PNNL discussed geophysical methods used at DOE and U.S. Department of Defense sites (ML22136A196). These geophysical methods can be used to determine areas of leaks or increased moisture content among other properties. The geophysical toolbox was discussed with emphasis on the use of geophysical tools in conjunction with conventional hydrologic measurements to enhance interpretation and inform conceptual site model development. Various technologies are available including seismic refraction and reflection, electrical resistivity tomography (ERT), ground penetrating radar, time-domain electromagnetics (TDEM), and conventional borehole logging. Measured properties include depth to bedrock/water table, water content, porosity, salinity, lithology, and transmissivity.

The presentation discussed the use of ERT on the surface to measure various subsurface properties influencing electrical conductivity (e.g., moisture content, porosity, conductivity, temperature, soil surface area, buried metal, and anomalous conditions). Typically, radionuclide concentration levels are not high enough to be picked up by ERT; however, a few examples demonstrating the use of ERT to pick up variations in moisture content associated with leaks and spills were presented. The first example was use of ERT to monitor Columbia River water infiltration near infiltration ponds that were a source of uranium to groundwater, as well as imaging of lithology (coarser gravel and cobbles and finer backfill material that had varying electrical conductivity). A second example provided a 3D image around cooling water discharge pipes at an operating nuclear power plant that showed discharge from a line located above the piping. The third example showed leakage and increasing moisture content/nitrate concentrations at the “B Tank Farm” at Hanford. The final example showed time lapse performance monitoring of remediation (coprecipitation of uranium via polyphosphate injections) near the Columbia River at Hanford. TDEM was also discussed. TDEM uses EM fields and a receiver loop to collect data over much larger areas compared to ERT, while still providing vary rapid (almost real-time) results. The advantage of TDEM is that it does not require coupling to the ground like ERT (i.e., it can be pulled by all-terrain vehicle or boat; or flown).

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 2013). 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 2013).

4.4 Demolition Impacts on CSM

The conceptual site model used to create a flow and transport model in RESRAD should reflect site conditions over the 1,000-year performance period. For some sites, the CSM and abstraction into a RESRAD-ONSITE model may change due to decommissioning.

Historical groundwater data may reflect the presence of buildings constructed below the saturated zone, pilings supporting those buildings, buildings in the zone of a fluctuating water table, and the degree of hard surfaces across the site. Historical groundwater data may exhibit the influence of these structures on groundwater flow. Removal of any of these structures may influence groundwater flow and transport. Excavation of buildings may change the flow conditions and transport characteristics at the site. For example, previously decommissioned sites have also breached the walls and floors of structures that were to remain in place such that natural flow and transport directions and magnitudes were no longer entirely impeded. Generally, the groundwater monitoring networks are not sufficiently positioned to quantify the impact of buildings and structures on groundwater flow and transport. Whereas some sites likely can qualitatively justify a minimal impact, there may be sites where either a conservative assumption should be made or an assessment and justification should be provided.

Additionally, removal of buildings and asphalt that cover a high fraction of the facility area can significantly change infiltration and recharge across the site. The CSM for the site may include a water balance analysis considering lateral and vertical contributions to saturated zone flow rates. Similarly, infiltration and recharge rates through the unsaturated zone should reflect the end state condition of the site.

Justification should be provided to support that the CSM is appropriate for the 1,000-year compliance period.

4.5 Groundwater Monitoring to Support Decommissioning

Surveys of groundwater and surface water are required during operations and decommissioning. A good understanding of residual radioactivity levels is essential when a licensee decides to cease operations. Based on the definition of residual radioactivity[18] in NRC regulations found at 10 CFR 20.1003, “Definitions,” the NRC regulates radioactivity in groundwater regardless of whether the material is licensed or unlicensed. Similarly, it is irrelevant if a release is accidental (e.g., a leak) or intentional (e.g., a planned discharge). Finally, it makes no difference if the licensee is a complex nuclear power plant or a single source material licensee; the same definition of residual radioactivity applies.

Additionally, under 10 CFR 20.1501, “General,” licensees are required to conduct surveys to determine, among other things, concentrations or quantities of radioactive material and potential radiological hazards. This requirement applies during operations and decommissioning. These surveys should be reasonable under the circumstances to evaluate groundwater radioactivity to

[18] 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.

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). ALARA requirements in 10 CFR 20.1402 also apply to exposures associated with groundwater contamination and must be met.

The NRC formed a Groundwater Contamination Task Force (GTF) due to incidents 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 GTF report provides an overview of facility operations related to groundwater contamination and the governing regulations for each type of licensee (NRC 2010). The different kinds and types of licensee operations will influence the approach and techniques to be used in the FSS.

There are many purposes associated with groundwater monitoring during operations and these purposes are likely to change as a site transitions from operations to decommissioning. An additional monitoring objective for decommissioning is site characterization of residual radioactivity in support of FSS dose estimates (NRC 2022). Groundwater monitoring objectives were discussed in more detail at the second subsurface workshop described in Section A.4, and include (i) monitoring the impacts of decommissioning activities on groundwater quality to assess risk to workers and members of the public, (ii) continued monitoring of the fate and transport of contaminants released to the groundwater table during operations, (iii) monitoring of groundwater contamination to assess the need for consultation with the U.S. EPA under the NRC/EPA MOU (Appendix H of NRC 2006b), (iv) monitoring changes in flow associated with decommissioning activities (e.g., before, during, or after dewatering or remedial activities), (v) performance monitoring associated with remedial activities, and (vi) assessment of water quality or field parameters for input to groundwater modeling, among others purposes.

Groundwater monitoring supports assessment of risk to members of the public following decommissioning. 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 NRC regulations in 10 CFR 20.1402 and 10 CFR 20.1403). To comply with these regulations, the licensee typically conducts sampling and monitoring to accurately define all radioactivity remaining on the site. Following remediation, as defined in the LTP or request for partial site release, groundwater should be sampled for residual radioactivity, according to an approved scheme, to demonstrate compliance with release criteria (NRC 2010).

The following two subsections provide discussions on two aspects of groundwater monitoring, the EPA/NRC MOU (Appendix H of NRC 2006b) and remediation during decommissioning.

4.5.1. Monitoring to Support the EPA/NRC MOU

As mentioned above, the NRC entered into an MOU with the EPA on cleanup of radioactively contaminated sites (Appendix H of NRC 2006b). This MOU includes provisions for NRC and EPA consultation for certain sites, including when contamination exceeds EPA maximum contaminant levels (MCLs) at the time of license termination. The EPA limits on drinking water are called MCLs for four groupings of radionuclides, as shown in Table 4.2. Table 4.3 provides derived values for several radionuclides based on the 4 mrem/yr limit for beta-photon emitters.

Table 4.2 U.S. EPA's MCLs

Radionuclide Maximum Contaminant Levels	
Beta/photon emitters	4 mrem/yr
Gross alpha	15 pCi/L
Radium-226 and radium-228	5 pCi/L
Uranium	30 µg/L

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), is used with certain assumptions regarding consumption rates to calculate the concentration leading to the 4 mrem/year standard. It is important to note that NBS Handbook 69 is based on old internal dosimetry found in ICRP 2. Therefore, the 4 mrem/year standard does not equate to 4 mrem/yr total effective dose equivalent (TEDE) and in many cases, significantly higher concentrations would lead to 25 mrem/yr (e.g., I-129 concentrations leading to 4 mrem/yr using updated dosimetry are more than an order of magnitude higher compared to the MCL).[19]
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[19] See National Primary Drinking Water Regulations; Radionuclides; Final Rule (65 FR 76707).

Table 4.3 Derived Concentrations from EPA MCLs for Beta and Photon Emitters

Radionuclide	pCi/L	Radionuclide	pCi/L	Radionuclide	pCi/L	Radionuclide	pCi/L	Radionuclide	pCi/L	Radionuclide	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	1-126	3	Gd-153	600	Pt-197	300
Cl-38	1,000	As-77	200	Ru-103	200	1-129	1	Gd-159	200	Pt-197m	3,000
K-42	900	Se-75	900	Ru-105	200	1-131	3	Tb-160	100	Au-196	600
Ca-45	10	Br-82	100	Ru-106	30	1-132	90	Dy-165	1,000	Au-198	100
Ca-47	80	Rb-86	600	Rh-103m	30,000	1-133	10	Dy-166	100	Au-199	600
Sc-46	100	Rb-87	300	Rh-105	300	1-134	100	Ho-166	90	Hg-197	900
Sc-47	300	Sr-85m	20,000	Pd-103	900	1-135	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		

4.5.2. Evaluation of Remedial Performance

Remediation of spills, leaks, or releases during decommissioning may require modifications to the groundwater monitoring network. Evaluation of the network design is needed to better facilitate performance monitoring. Evaluation of the remediation approaches and duration includes remediation objectives, site investigation criteria, and likely release limits reflected in the allotted dose for existing groundwater contamination. The objectives should address ALARA requirements. Considerations in the evaluation process should include the (i) potential for offsite migration of contamination, (ii) potential impacts to decommissioning planning, and (iii) potential to exceed release criteria for FSS.

Aspects of a good monitoring program can be derived from a study conducted by Brookhaven National Laboratory on lessons learned associated with its monitoring and modeling program of tritium and strontium plumes from past operations. These lessons learned are found in NUREG/CR-7029, *Lessons Learned in Detecting, Monitoring, Modeling and Remediating Radioactive Ground-Water Contamination*, issued April 2011 (NRC 2011). Figure 3.1 shows the basic steps in developing a remediation strategy. Lessons learned include the following:

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 groundwater should be removed as soon as possible since delays can lead to extensive and more complicated cleanup.
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. 2012; NRC 2011).

5. EXAMPLES AND LESSONS LEARNED

The following examples provide some lessons learned from previous reviews of LTPs, DPs, and final status survey reports.

5.1 Cumulative Risk from Multiple Contaminated Media

5.1.1 Consideration of Risk from Residual Radioactivity in Backfill Soils

In one example, subsurface soil DCGLs were derived for residual radioactivity in the unsaturated zone below excavated waste trenches. The DCGLs were based on a contaminated thickness equal to the thickness of the vadose zone below the trenches. The dose modeling analyses used to calculate the subsurface DCGLs assumed that the excavated soil would be backfilled with “clean” soil, meaning soil free of residual radioactivity above background. However, slightly contaminated soil located between disposal trenches and in the “clean” cover above the excavated materials were stockpiled and surveyed for reuse. The criterion for reuse was residual radioactivity that was less than the subsurface soil DCGLs, which is inconsistent with the dose modeling assumption that the reuse soils would have “zero added residual radioactivity.” Furthermore, no DCGLs had been derived for surface soil materials, which may be more restrictive compared to subsurface DCGLs for radionuclides dominated by surface exposure pathways.

If a licensee chooses to develop a single soil DCGL to account for both surface and subsurface residual radioactivity, the total thickness and the depth of residual radioactivity needs to be considered (in this example the total thickness of residual radioactivity would have been greater and the depth below land surface lower), potentially leading to significantly lower DCGLs for certain radionuclides dominated by surface pathways (external dose and plant ingestion).

Two important points can be made: (1) the cumulative risk from all contaminated media needs to be considered (dose from both the subsurface soils located below the disposal trenches and the dose from the reuse of soil closer to the surface), and (2) surface and subsurface DCGLs may be significantly different—DCGLs are a function of depth and thickness of contamination (dose modeling assumptions should be consistent with the final configuration of residual radioactivity remaining at the site to support the compliance demonstration).

5.2 Remedial Action Support Survey (RASS)

5.2.1. RASS to the Quality of an FSS

In some cases, excavations have been conducted and excavations have been backfilled with insufficient survey data provided to support release of a Class 1 area. As stated in Appendix G to NUREG-1757, Volume 2, Rev. 2 (NRC 2022), it is expected that the open surfaces of an excavation will be surveyed prior to backfilling to support the FSS for release of the survey unit and that floors of excavations will typically be Class 1 survey areas due to the need for remediation to meet the release limits (i.e., potential for soil to be above the action levels). Survey of the excavation floors and walls is expected because scan surveys cannot be performed for excavation surfaces following backfill.

In some cases, prompt backfilling of the excavation may be necessary for safety or other reasons (prior to confirmatory survey and more extensive RASS). In these cases, the licensee should adequately plan to ensure that these cases are limited, that mitigative measures are appropriately considered and taken to ensure adequate survey to support release of the survey unit(s), and that the NRC is consulted in advance to provide an opportunity for confirmatory or other verification surveys as practical. See additional discussion in Sections 2.8 and 2.10.

5.2.2. Tracking of Contaminated Materials During Demolition

In one example, a portion of a contaminated concrete foundation was buried below the surface of the excavation unbeknownst to the operator during demolition activities. A lack of oversight and radiation protection coverage was also identified by the licensee as a lesson learned. A confirmatory survey performed by an NRC inspector in the region identified elevated readings, which led to further excavation and identification of additional residual radioactivity. Ultimately, a significant quantity of additional concrete debris and soil above operational DCGLs was removed from below the excavation. The licensee entered the issue into its correction action program. Corrective action included the short-term stoppage of all demolition and FSS activities, revisions of procedures, and discussions with demolition and radiation protection staff. The licensee took 15 new systematic geoprobe samples in the soil excavation area. Work packages were revised to require the measurement and documentation of the depths of excavations. Additionally, a requirement was added to dig out/sift at a minimum of three feet below the bottom of the concrete slab being removed.

5.2.3. Survey of Subsurface Soils Below an Excavation

In another example, a request was made by a licensee to amend a DP to reduce the number of samples based on a check and cover method example provided in NUREG/CR-7021 (see Figure 3.5 in NUREG/CR-7021). The NUREG/CR-7021 example is just an example and is not applicable to all sites and should not been used without further analysis and support. Further, although the original DP proposed to sample the vadose zone from the bottom of the excavation to the water table aquifer, relief was requested to allow geoprobe samples to terminate directly below the excavation. The sampling plan in the original DP recognized the presence of historic groundwater contamination that migrated from the source area, through the vadose zone, and to the groundwater aquifer and contained deep vadose zone sampling provisions to confirm that there was no risk-significant subsurface residual radioactivity remaining. Results provided in the FSS showed elevated readings in groundwater of a known ROC at the site. Additionally, the minimum detectable concentrations for the groundwater sampling where the elevated readings were reported were orders of magnitude higher than risk-based levels and would not satisfy DQOs for groundwater sampling. The elevated readings found in the groundwater sampling were originally dismissed as being anomalous due to high turbidity without further discussion or investigation. The licensee later confirmed low levels of residual radioactivity at the locations of the previous elevated readings. Nonetheless, NRC notes that following issues with the FSS including the following:

1. Lack of support for the number of samples below the excavation;
2. Lack of support for the depth of samples (at a site with known groundwater contamination, only a small portion of the vadose zone underneath the source areas was sampled (e.g., around 0.3 m));
3. MDCs for groundwater samples taken below the source area were orders of magnitude higher than risk-based levels; and
4. Significant levels of radionuclides of concern were detected in groundwater, which were ruled out as anomalous due to high turbidity but were not resampled and investigated.

5.3 Challenges with Survey of Small Excavations

An example of a small excavation at a power plant is a sump located at a lower elevation than the associated building floor. Such structures lead to small, deep, steep-walled survey units that have been backfilled without FSS scans or sampling. These small decision units have not been surveyed due to issues such as (i) steep side walls and use of steep support boxes for trenches, (ii) flooding due to groundwater influx when the excavation is below the water table, and (iii) ground support needed for machinery on adjacent structures. In some cases, the entire survey unit or large portions of the survey unit may not be accessible to survey per MARSSIM requirements. Four lessons learned are discussed below.

1. Mitigative measures to reduce the influx of groundwater or improve the geometry of the excavation to allow survey should be considered. If a sufficient area of the survey unit is unable to be scanned per the MARSSIM classification requirements due to geometry or other physical constraints, then this limitation should be considered as part of the DQO process described in Section 2.6.1 above.

2. In some cases, RASS to the quality of an FSS is not conducted prior to backfill of excavated soils. In one case, the FSS data was collected following backfill and consisted of scanning and sampling of Geoprobe cores obtained to a depth slightly below the excavation surface. Scans of cores missed residual radioactivity shown to be above operational DCGL values based on comparison with results from composite samples. This may be mitigated by developing or improving scanning procedures for Geoprobe cores that includes validation of the survey method. See also Section 2.5 on “small decision units.”

3. Excavation surface elevation needs to be obtained and included in report documentation. Elevation information should be of sufficient quality to help identify the excavation surface in Geoprobe cores. In addition, small excavations may be part of larger excavations, with a variable depth of excavation. Descriptions of overlapping survey units should include both the elevation information and the chronology of the excavations.

4. Isolation and control should be maintained if the FSS is completed for vertically overlapping survey units prior to survey of the lowest excavation or survey unit. In one instance, the sump excavation survey unit overlapped vertically with two other survey units. The sump was excavated after FSS was completed on overlying survey units, which invalidated the FSS data for the overlying survey units. Because the area of the overlying survey units changed when the sump was removed, the statistical validity of the remaining FSS data in the overlying survey units had to be reassessed.

See Section 2.7 for guidance related to subsurface sampling, which may mitigate some of these technical challenges and issues.

5.4 Balance of Information to Provide in DP/LTP and FSS Reports

The balance between too much and not enough information in DP/LTPs and FSS reports is often discussed by both licensees and NRC staff. Not enough information can lead to requests for additional information (RAIs), follow-up questions, and supplemental requests that can extend the length of time needed for staff review. Too much information leads to DP/LTPs and FSS documents that are thousands of pages long, thus possibly requiring substantially more staff resources to review and obscuring important discussions. Whereas subsurface investigations may include more innovative approaches and unusual or atypical situations compared to surface investigations, the right balance of information is an issue of concern for subsurface submittals.

Pre-submittal meetings may be useful to licensees to help them better understand the NRC's expectations with respect to the level of detail needed in compliance documentation. Innovative approaches, unusual or atypical situations, or abnormal situations during decommissioning are likely to lead to RAIs if descriptions, reconciliations, and supporting data are not provided in sufficient detail. Some of the lessons learned examples in Chapter 5 may be described as innovative, unusual, or atypical. For routine survey units, brief standardized reports are likely adequate. The level of detail should use a graded approach, considering the residual radioactivity levels, as well as atypical events that may have occurred or anomalies present in the data.

Additionally, some licensees have used the DP/LTP to provide a complete picture, while other licenses have shortened the LTP by citing documents by reference instead of summarizing the information from the supporting document. Incorporation by reference refers to a subsection of the DP/LTP simply being a sentence pointing to another technical basis document. Either approach is acceptable to NRC staff if the needed information is provided by the licensee either in the main or supporting document. The advantage of the former approach is that a complete and coherent picture is provided in the DP/LTP, which is a benefit to both the licensee and NRC staff reviewers and to future decision makers and stakeholders at partial site release, license termination and beyond. The advantage of the latter approach is that a shorter DP/LTP is generated and there is less likelihood of inconsistencies being created. However, providing information by reference to technical basis documents results in those documents also becoming part of the licensing information that will be assessed by NRC staff during the FSS (i.e., licensing documents). Therefore, revisions to these documents and approaches should be discussed with NRC staff to ensure that the changes do not impact the prior approval of the DP/LTP. These discussions could lead to the need for license amendments.

6. SUMMARY AND CONCLUSIONS

This ISG provides guidance on surveys of open surfaces in the subsurface, including surfaces of open excavations, substructures, and materials planned for reuse where widely accepted MARSSIM approaches that have proven effective for surface survey problems can be extended. The guidance represents the NRC's efforts to develop subsurface guidance to inform radiological survey, conceptual site model development, and assessment of risk from subsurface residual radioactivity. The NRC plans to address comments on this draft ISG in a comment response document and issue a final ISG. The final document will be incorporated into the next version of NUREG-1757, Volume 2 (currently planned on a 5-year revision cycle or to be updated in 2027). Table 6.1 provides a crosswalk between the ISG guidance and NUREG-1757 and other guidance documents.

Table 6.1 Crosswalk Between this ISG and Future Guidance Documents

Chapter	Chapter Scope	Plans for NUREG-1757, Volume 2, Rev. 3
1	Chapter 1 and Appendix A of this ISG provide background information on the technical issues and complexity associated with subsurface residual radioactivity.	Portions of Chapter 1 and Appendix A material may be included in a new appendix on subsurface investigations.
2	Chapter 2 of the ISG provides detailed guidance on application of MARSSIM principles to open surfaces in the subsurface including classification, subsurface survey unit size, sampling and scanning strategies and hypothesis tests, as well as information on instrumentation and detailed examples linking the information together in a cohesive fashion.	Subsurface information from Appendix G of NUREG-1757, Volume 2, Rev. 2 (e.g., Section G.3) and material from Chapter 2 of this ISG will be merged into a new Appendix on subsurface investigations.
3	Chapter 3 of the ISG provides guidance on the use of RESAD-ONSITE, a commonly used decommissioning dose modeling code, to develop DCGLs for submerged sources such as basement substructures. Chapter 3 also contains additional information on when additional support for risk-significant parameters such as K_d are needed and how that support can be provided.	Information in Chapter 3 will be folded into Appendix I of NUREG-1757, Volume 2.
4	Chapter 4 provides information on calculation of pathway dose conversion factors for groundwater, and methods to assess risk from existing groundwater contamination. Additional guidance on groundwater monitoring consideration is also provided.	Information in Chapter 4 will be folded into Appendix F of NUREG-1757, Volume 2.

5	Chapter 5 provides lessons learned and context for some of the new ISG guidance.	Lessons learned are reflected in new ISG guidance which will be folded into NUREG-1757, Volume 2 as described in this table.
Appendix A	Appendix A discusses NRC staff's early efforts to develop guidance in this area, and NRC staff's long-term plans to address remaining issues.	Portions of Appendix A may be included in the new appendix on subsurface investigations.
Appendix B and C	Appendix B and C provide information on current tools available for data visualization and survey design optimization as well as details on NRC's current and future efforts to develop additional guidance and tools during Phase 2 of subsurface interim guidance development.	NUREG/CR-7021, Rev. 1, will provide an updated methodology for subsurface survey design, remedial and compliance decision-making support. VSP tools are being developed in conjunction with the guidance update. A summary of this work will be provided in the new subsurface appendix that will incorporate information from the subsurface sections in NUREG-1757, Volume 2, Rev. 2, Appendix G, and Chapter 2 of this ISG.

7. REFERENCES

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APPENDIX A

Current Guidance

A.1 NUREG-1575, Rev. 1 (and Draft Rev. 2) Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)

MARSSIM, Rev. 1 and draft Rev. 2, provides guidance on radiological surveys during all phases of the radiological survey and site investigation process (historical site assessment (HSA), scoping, characterization, remedial action support surveys (RASS), and final status surveys (FSSs)), focusing on FSSs to demonstrate compliance with dose- or risk-based release criteria. MARSSIM only addresses surface contamination (within the first 15 cm of soil or building surfaces). Nonetheless, the principals in MARSSIM can be applied to surfaces in the subsurface (e.g., survey of excavated soil during remedial activities, survey of building substructures, survey of soil planned for reuse in open excavations or subsurface structures).

A.2 NUREG-1757, Volume 2, Rev. 2, Consolidated Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Criteria

A.2.1 Appendix G, Special Issues Associated with Dose Modeling, Characterization, and Survey

NUREG-1757, Volume 2, Rev. 2, Appendix G, contains information on use of geographical information system (GIS), geostatistical, and other data visualization and analysis tools that may aid development of site conceptual models, survey design, and demonstration of compliance with release criteria. Appendix G contains information about survey of open excavations, as well as surveys associated with reuse of materials with onsite and offsite materials used for backfill. Appendix G also contains information about consideration of risk from multiple contaminated media, including the application of multiple DCGLs, which may be needed to adequately assess risk from surface and subsurface soils. Information on dose modeling considerations for subsurface soils was also included in Appendix G based on information obtained from the first subsurface workshop held in May 2021, as well as major findings from the workshop and a list of challenges and lessons learned associated with survey of excavations. This information is supplemented with more detailed guidance in Chapter 4 of this ISG on survey of open excavations, reactor basement and other substructures and materials planned for reuse, including the applicability of MARSSIM statistical tests and alternative methods that may be appropriate in certain cases.

A.2.1.1 Appendix J, Exposure Scenarios for Buried Radioactivity

NUREG-1757, Volume 2, Rev. 2, Appendix J contains information on the types of exposure scenarios that may need to be considered for buried residual radioactivity. Residual basement construction is typically considered for residual radioactivity located within 3 m (10 ft) of the surface[20]. For deeper residual radioactivity, other scenarios may be considered such as well drilling or a large construction project. Chapter 5 of the guidance document provides information on consideration of reasonably foreseeable future land use, as well as less likely but plausible exposure scenarios that may be considered to risk-inform the decision. Implausible exposure scenarios can be excluded from consideration. In situ leaching of residual radioactivity should also be considered if groundwater dependent pathways are viable.

[20] Residual radioactivity occurring in the top 3 m of soil considering erosion reducing the cover thickness over a 1,000-year compliance period.

A.3 NUREG/CR-7021, A Subsurface Decision Model for Supporting Environmental Compliance

NUREG/CR-7021 contains a geospatial modeling and decision framework for conducting subsurface compliance surveys. Published in 2012, this report was prepared under contract by Robert Stewart of the University of Tennessee and combines the principles of MARSSIM with the use of conceptual site models. As part of this research project, the contractor modified an existing software package called Spatial Analysis and Decision Assistance (SADA) to implement new numerical tools for use in subsurface characterization. Specifically, the SADA software provided several informed initial design strategies, in which conceptual site models were used to assist in survey design. Within these proposed survey designs, the paper developed a novel CSM which it referred to as a "contamination concern map" (CCM). The CCM described the extent, location, and significance of residual radioactivity relative to the decision criteria. NUREG/CR-7021 was further advanced by Robert Stewart's follow-on dissertation work (Stewart 2011) which provided a consistent workflow from historical site survey to compliance testing including new optimization approaches for sampling and compliance confirmation.

Although NUREG/CR-7021 outlined a methodology for demonstrating compliance with the NRC's license termination rule criteria and recommended tools in the SADA computer code to support each phase of the radiological survey and site investigation process, the work was never fully incorporated into Federal agency guidance. Challenges to the successful implementation of the methodology in NUREG/CR-7021 to subsurface problems include the complexity associated with geostatistical modeling, uncertainty in compliance decision-making, and the adequate assessment of cumulative risk from multiple sources, among others. In 2019, the NRC reinitiated work to develop guidance in this area. A contract was awarded to SC&A to address subsurface survey and dose modeling issues. SC&A produced a technical white paper that is discussed in greater detail in Section A.6.1 (SC&A 2022). Long-term plans are to update NUREG/CR-7021 considering information sources completed after issuance of the NUREG and implement proposed algorithms and tools to support compliance decision-making in the Visual Sample Plan (VSP) computer code as discussed in Appendix A.6.2 and B.3.

A.4 Comments on Draft NUREG-1757, Volume 2, Rev. 2

The NRC solicited comments on draft NUREG-1757, Volume 2, Rev. 2. Comments on draft NUREG-1757, Volume 2, Rev. 2, are listed below. The responses to the comments are found in ADAMS at Accession No. ML21299A032.

1	A comment was made that use of multiple DCGLs when subsurface residual radioactivity is present adds complexity, implying that use of multiple DCGLs should be avoided. *The response indicated that in some cases multiple DCGLs are needed to accurately assess risk from subsurface residual radioactivity and cited presentations at the first subsurface workshop by Barr and Yu (2021) related to sensitivity analysis on parameters important to subsurface DCGL development. These presentations are discussed in Section G.3.1 of NUREG-1757, Volume 2, Rev. 2. Additional guidance was also provided in Section G.3.6 on the acceptability of use of the most conservative DCGL to directly address this comment (provided concentrations are not artificially diluted in thicknesses of residual radioactivity that are most sensitive to dose).*
2	A comment was made that scenarios that could bring residual radioactivity to the surface should be considered. *The response indicated that Appendix J provides guidance on potential exposure scenarios that could bring residual radioactivity to the surface that should be considered for buried residual radioactivity.*
3	The need for guidance on use of geostatistical and other tools for subsurface survey design including examples for buried waste at the U.S. Department of Defense and former NRC/AEC licensees, and commercial nuclear reactors. *The response indicated that work was ongoing in this area, that NRC was sponsoring subsurface workshops to discuss methods and tools, and that additional guidance would be forthcoming.*
4	The need for guidance on survey of hard-to-detect (HTD) radionuclides in the subsurface. *The response indicated that additional guidance would be forthcoming.*
5	The need for development of a contamination concern map (CCM) as indicated in NUREG/CR-7021. *The response indicated that a CCM would not be required. The guidance provided in NUREG/CR-7021 presents one acceptable approach to assist with survey design, remedial and compliance decision-making.*
6	Necessary sampling density for residual radioactivity in the subsurface. *The response indicated that guidance was provided in Appendix G and that additional guidance was forthcoming.*
7	Guidance on use of in situ gamma spectrometry as a method for performing radiological surveys of open excavations. *The response indicated that in some situations use of in situ gamma spectrometry would be found to be acceptable by NRC staff (e.g., for worker safety concerns). The response also indicated that additional guidance in this area would be provided.*
8	Survey requirements for off-site soil reuse. *The response indicated that when there was a reasonable concern that the soils were impacted, that a Scenario B type or other analysis could be performed to provide support for the reuse of soils. The guidance was softened to state that "support" should be provided to show that the reuse soils are non-impacted versus "an analysis should be performed."*
9	The need for reuse plans in decommissioning and license termination plans. *The NRC staff agreed that reuse plans should be clear and that the comment would be forwarded to the NUREG-1757, Volume 1 working group for inclusion in the Appendix D checklist.*

10	Guidance on how to survey walls of an excavation where sheet piling is used. *The response indicated that the guidance would be updated to reflect the fact that in some cases sidewalls may be inaccessible for direct survey/sampling (e.g., sheet pilings are used to shore up excavation side walls).*

Comment	NUREG-1757, Vol. 2, Rev. 2	Interim Staff Guidance
1 (Multiple DCGLs)	Appendix G	Section 2.9; Section 3.5.2
2 (Scenarios)	Appendix J	Section 3.4
3 (Geostatistics)	Appendix G, J	Appendix B and C
4 (HTD)	N/A	Chapter 2
5 (CCM)	Appendix G (not a requirement but App. G indicates it can be useful)	N/A
6 (Sample Density)	Appendix G	Section 2.5 and 2.7
7 (ISOCS)	Appendix G	Section 2.6.2
8 (Reuse Surveys)	Appendix G	Chapter 2
9 (Reuse Plans)	Appendix G	N/A (Volume 1)
10 (Survey Challenges)	Appendix G	Sections 2.5 and 5.3

A.5 <u>Subsurface Workshop Summary</u>

A.5.1 Subsurface Workshop (July 2021) https://www.nrc.gov/docs/ML2130/ML21300A378.pdf

The first workshop was held virtually on 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, presentations on industry needs with respect to such guidance, and the current experience with geospatial and statistical-based surveys of subsurface soil. Over 195 people registered to attend this workshop with approximately 67 from state agencies, 48 from industry and commercial companies, 36 from non-NRC federal organizations, 33 NRC staff, 8 from the public, and 3 from international organizations.

Discussion during the first workshop covered a wide range of issues for consideration when surveying the subsurface, including the need for a solution that is not overly complex and the need for 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 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.

Conclusions and findings from the 2021 workshop include the following:

- Electric Power Research Institute (EPRI) Report 1013511, "Connecticut Yankee Decommissioning Experience Report: Detailed Experiences 1996-2006," issued

November 2006, discusses a case study for a site with significant subsurface contamination. Direct push samples and core drilling of bedrock were used to extract cores or to facilitate down-hole gamma logging. Areas above the DCGLs were remediated through excavation. Portable gamma spectroscopy equipment was used to survey the bottom of the bedrock excavation. There was concern about missed activity in bedrock, so the licensee used a graded sampling approach approved by the NRC. HTD radionuclides were present.

- EPRI Report 3002007554, “Guidance for Using Geostatistics in Developing a Site Final Status Survey Program for Plant Decommissioning,” issued May 2016 provides a review of geostatistics software, including Visual Sample Plan (VSP) and SADA, as well as a summary table. The EPRI report provides a roadmap for applying geostatistics, including major phases of geostatistical analysis, steps within each phase, and key questions associated with each step.

- Geostatistical approaches have a long history in non-radiological applications and have been developed in the mining industry for characterization, for example. However, one example of a radiological application is at the Fontenay-aux-Roses site in France (see Section 4.3 of EPRI 2016). The site had a relatively thin layer of contamination along a vertical gradient along the bank of a former moat. Initial drill hole campaigns for cesium-137 were used to develop a three-dimensional kriging map, which in turn informed additional sampling campaigns and development of a remediation plan.

- A geostatistical approach has been used at both excavated and nonexcavated sites. Any area with three-dimensional contamination, such as contaminated concrete, could benefit from geostatistics. It may also be useful for designing sampling plans and to guide remediation.

- Geostatistics is just one tool to address subsurface problems. Supplemental information about physical boundaries and contaminant transport should be considered in developing a spatial model to ensure that unrealistic results do not occur. Leveraging expertise in multiple disciplines and relying on more than one tool will help limit decision errors and lead to more stable decision-making.

- In the past, characterization was more reactive. If there was a concern about impacts to the environment or exposure to members of the public, a team would mobilize to the site, dig things up, and take soil borings that were then sent off to a laboratory. The laboratory results would come back, and the results would be assessed. Often the extent of contamination was not bounded, or the source had not been identified. Perhaps some remediation would take place and remobilization and resampling would occur. This process would be repeated until the site was found to be clean. While often effective for certain project goals, the process was drawn out and expensive.

- Regulations that required better recordkeeping and advancements in technologies made the decommissioning process more efficient. For example, advancements in field measurement technologies have allowed more measurements and decision-making in the field during assessment and remediation. This is formalized in the U.S. Environmental Protection Agency’s Triad approach with (1) systematic planning (i.e., HSA, development of the conceptual site model), (2) dynamic work strategies, and (3) real-time measurements (using mobile laboratories and instrumentation, remote sensing, and GPS/GIS data to create a digital twin of the site).

- The Common Data Environment (CDE) represents an investment in characterization to reduce remediation and waste disposal costs. It includes a living conceptual site model that contains GIS information/models (e.g., risk ranking of systems, structures, and components (SSCs), land use, hydrogeological data, Light Detection and Ranging (LIDAR) integrated with a building information model that has architectural, mechanical, and structural facility data embedded in a three-dimensional digital twin. The Nuclear Energy Institute (NEI) SSC risk ranking guidance (NEI 09-14, "Guideline for the Management of Underground Piping and Tank Integrity," and NEI 07-07, "Industry Ground Water Protection Initiative—Final Guidance Document") provide the data to input into the GIS and building information model. Nuclear facilities have design controls and extensive documentation that makes them well suited to use the CDE, which can be employed to know what is happening at different plant locations even after the structures themselves are gone. Once set up, the site model can be used when needed to investigate issues even before decommissioning and can be modified rapidly when needed.

- The CDE approach is data intensive and the software tools can be expensive, so it may not be a solution for smaller sites, but data from larger sites, such as reactor decommissioning sites, could be leveraged to construct a CDE.

A.5.2 Subsurface Workshop (May 2022)
https://www.nrc.gov/docs/ML2214/ML22143A891.pdf

The second workshop was held virtually on May 11, 2022. It began with NRC presentations on the agency's efforts in this area to date, including related decommissioning guidance, currently available subsurface guidance, key guidance gaps, and plans for issuance of additional interim guidance. Approximately 130 stakeholders participated in the workshop with representatives from Agreement States, industry organizations, various licensees, and attendees and speakers from DOE national laboratories and other research organizations. The NEI discussed its plans to develop NEI 22-01 to standardize the format and content of information to be submitted to the NRC (e.g., FSS data) to support license termination and shorten decommissioning timelines. Other technical presentations topics and findings included the following:

- SC&A presented on statistical methodologies currently under consideration, specifically describing two features in the 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 HSA, 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 (DQA), 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 (RSCS) 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 uses 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.

- RSCS also provided a historical perspective of survey and dose modeling of reactor basement substructures, including activities at the Connecticut Yankee, Yankee Rowe, and Maine Yankee nuclear power plants (NPPs), which were some of the first applications of the license termination rule and MARSSIM methodologies in the early to mid-2000s. Important differences between license termination for earlier versus later examples were provided. One significant difference was the lack of consideration of intrusion events that could bring radioactivity to the surface, which was applied in the Zion and La Crosse cases. Another significant difference was the treatment of the basement substructures as MARSSIM Class 1 areas that necessitate 100 percent scan surveys of the surfaces, leading to hundreds of measurements or more. Arguments were presented that a conservative estimate of the total inventory could be developed using more practical characterization survey methods focusing on elevated areas, rather than using statistically based approaches laid out in MARSSIM. The need for 100 percent scan surveys of surfaces that would be backfilled, thereby limiting the potential exposure risk from these surfaces, was unclear, with RSCS noting that the likelihood of large-scale excavation of soil or building structures was low. For subsurface soil, RSCS indicated that 100 percent coverage is not possible or needed and geostatistical interpretation can be used to fill in data gaps due to the inability to scan.

- The U.S. Department of Energy (DOE) discussed DOE Order 458.1, "Radiation Protection of the Public and Environment", for the release of personal property such as materials and equipment (10 μSv/yr or 1 mrem/yr) and real property such as land and fixed structures (0.25 mSv/yr or 25 mrem/yr) and associated dose constraints. A case study was provided for a parcel of land at the Los Alamos site that was remediated for transfer back to the county. In 2020, radioactively contaminated metal objects and other materials were discovered but expected to pose little to no risk. The importance of HSA was stressed to ensure that areas with potential buried residual radioactivity are identified and properly assessed.

- 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 (ERT) 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.

Discussion periods were built into the agenda for the second subsurface workshop with focused questions. Key comments included the following:

- Several comments were made regarding the need for practical approaches. Because most sites do not need to use these complex subsurface methods, the guidance should be clear on when a site would need to enter this space and when it did not.

- Some participants commented on the need for consensus guidance instead of the case-by-case approach that can lead to less effective decision-making.

- Industry discussed the need for additional guidance on survey of reactor substructions that are not technically Class 1 MARSSIM survey units since they are located below grade in the subsurface. Industry representatives indicated that there is no need for 100 percent scanning and the survey should focus on elevated areas using walk-over surveys with gamma detectors, direct measurements, and sampling to develop a conservative estimate of the total inventory. New technologies include gamma spectroscopy coupled with LIDAR that can be used to detect elevated areas in lieu of 100 percent scan surveys. Chapter 4 provides additional information on substructure survey design and FSS considerations, including information on use of alternative technologies.

- Comments were made about the change in monitoring objectives when a site transitions from operations to decommissioning, as well as from remediation to FSS. In some situations, wells need to be removed to facilitate decommissioning activities or to prevent contamination of aquifers. New wells are often installed to monitor decommissioning activities. Termination of dewatering systems used during operations can lead to changes in groundwater flow directions and contaminant fate and transport and is also an important consideration. Chapter 6 provides additional information about groundwater monitoring programs and design.

- A question was raised by a member of the public regarding how groundwater contamination is considered as part of the decommissioning process and if unacceptable levels are found, the types of groundwater remediation technologies that are considered. Chapter 6 provides additional information about groundwater monitoring, including remedial and performance monitoring, and how the risk of existing groundwater contamination is considered as part of the license termination process.

  The presentations and meeting summary for the second annual subsurface investigations workshop can be found at ADAMS Accession No. ML22117A070.

A.6 Contractor Technical Reports (SC&A White Paper and PNNL Scoping Report)

A.6.1 SC&A White Paper (SC&A 2022) https://www.nrc.gov/docs/ML2227/ML22277A549.pdf

Published in 2022, this white paper from NRC contractor SC&A Inc. acts as follow-on research from the earlier work detailed in NUREG/CR-7021. In the 2022 white paper, SC&A summarizes technical efforts focused on assessments of radiologically contaminated subsurface soil. Most chapters of this paper amount to an expansive literature review with recommendations and expert commentary provided by SC&A technical staff. This white paper was able to capture and summarize progress and case studies in the decade since the publication of NUREG/CR-7021.

The SC&A white paper also identifies existing 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 uncertainties. Topic areas of this white paper include (i) stages of subsurface decision framework, (ii) geospatial modeling tools, (iii) statistical tests, (iv) evaluations of large soil excavations, (v) autonomous vehicles, (vi) treatment of uncertainty, (vii) hot spots, and (viii) subsurface derived concentration guideline levels (DCGLs).

The white paper appendix goes into further detail in these topic areas listed above while including new remediation case studies, survey designs specific to VSP and SADA codes, and summaries of conveyorized survey monitors. This extensive report provides critical guidance to the NRC because it summarizes industry-accepted practices and references for NRC-proposed activities, including historic applications, all focused on subsurface soil. In addition, the white paper provides input on potential statistical limitations that would be encountered in applying existing approaches to the subsurface.

A.6.2 PNNL Subsurface Scoping Report (PNNL 2022) https://www.nrc.gov/docs/ML2236/ML22363A001.pdf

PNNL was tasked with considering the recommendations in the SC&A white paper discussed in Section A.5.1, as well as making its own recommendations for tools to be added to the VSP software to facilitate subsurface investigations and decision-making. PNNL published a scoping report providing these recommendations along with a review of analytical methods applicable to the subsurface. The report identifies updates to VSP software in support of subsurface compliance phase survey design and geostatistical analysis considering subsurface complexities and practical constraints on survey sampling. It prioritizes VSP updates based on current capabilities, the ease of expanding them from two dimensions to three dimensions, requirements for new algorithm development, and the applicability of each method to compliance phase activities.

APPENDIX B

DATA VISUALIZATION AND ANALYSIS

B.1 Introduction

This chapter briefly discusses tools available in various computer codes for data visualization and analysis. These tools are essential for geospatial analysis of radiological survey data and development of a site conceptual model as described in Section G.3.1 of NUREG-1757, Volume 2, Rev. 2; and Section 8.2 of MARSSIM, Rev. 2. It is important to note that the statistical tests in MARSSIM, Rev. 2, are not spatially aware, and therefore, MARSSIM encourages the use of these types of tools to better understand spatial trends in the data, which may be informative to delineation of survey units, better understanding background variability and population characteristics, as well as assisting with conceptual and mathematical model development.

Several GIS and geostatistical tools and associated software are available to assist with designing, performing, and evaluating the results of radiological investigations. As stated above, 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 to assist with delineation of survey units. Geostatistical tools can also 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 to define the nature and extent of residual radioactivity.

Data exploration tools for subsurface characterizations often include 2D and 3D data visualization options. These tools are critical for the development of accurate conceptual site models. With the aid of visualization software, 2D or 3D information can be imported and then presented as multiple slices (layers) or by volume. Once imported, this data can also be used in geostatistical analysis and interpolations. This report section highlights two software applications with these visual and analytical capabilities: SADA and VSP. Both SADA and VSP incorporate visualization tools, and both contain sample designs that have the objective of better defining the border (or contour) of a chosen parameter (e.g., residual radioactivity) at a specified level. 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.

It is important to note that SADA is not currently supported or maintained, whereas VSP is currently supported and maintained by PNNL. Therefore, current plans are to update the VSP computer code to include additional data visualization, geospatial modeling, and data analysis tools to facilitate compliance decision-making for complex decommissioning sites with significant quantities of subsurface residual radioactivity as described in Section A.5.2 of this ISG.

B.2 SADA

SADA is a software package that 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. This software was developed as a collaboration between the University of Tennessee and Oak Ridge National Laboratory. SADA was the focus of previous NRC-supported research reported in NUREG/CR-7021. In addition to modules on MARSSIM analysis and secondary sampling design, SADA includes basic GIS capabilities to manage different layers or to define user-defined areas or polygons that may be used in downstream analysis.

Potential SADA applications 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 the costs for remediation to the different cleanup levels.
- Selecting optimal sampling locations and placing them on a site map.
- Selecting coregionalization modeling options (e.g., linear, intrinsic, and Markov models of coregionalization) to facilitate the development of cokriging variograms (see SADA User Guide).
- Creating variograms surfaces along any plane (see Figure B.1 Rose Diagram below).

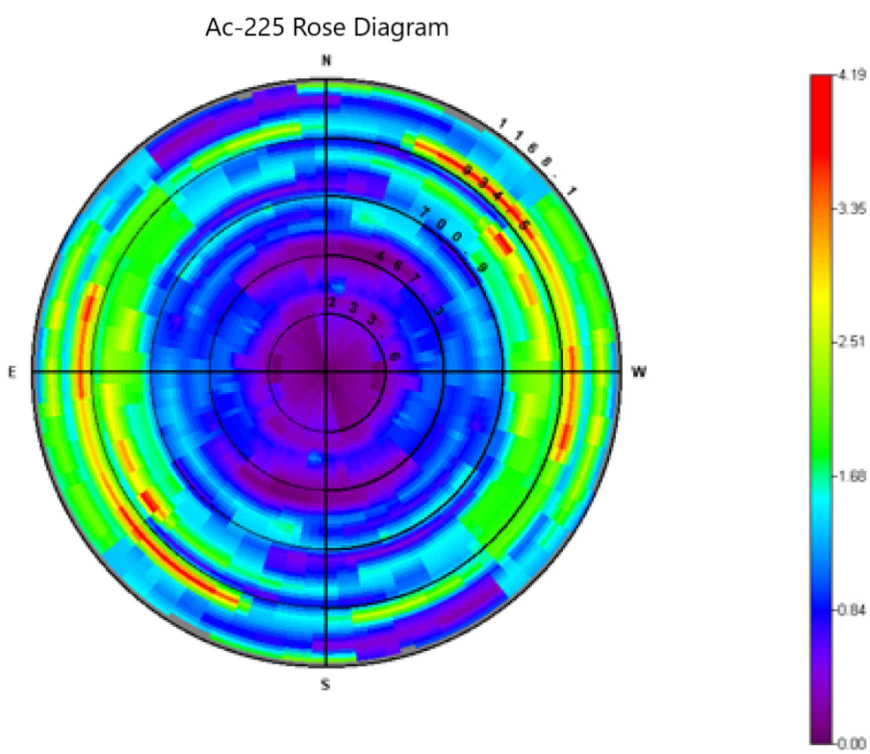

Figure B.1 Variogram Surface from SADA

SADA's geostatistical capabilities include some of the following features:

- Generating maps (2d and 3d) for kriging mean, kriging variance, geostatistical simulations, and decision support summaries such as probability of exceeding a threshold,
- Producing semi-transparent color maps, isosurfaces, and sample location renders,

- Generating 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.

SADA's visualization capabilities include the ability to accept map layers from GIS which allow 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 2009)). Additional tools in a beta version of SADA evaluated in Stewart (2011) are also being considered for incorporation into the VSP computer code described in the next section.

B.3 VSP

VSP is a software package that can be used to design an optimal, technically defensible sampling scheme for characterization. VSP was originally developed by PNNL for environmental management applications, with specific focus on sample design. VSP has been used in the context of radiological site characterization at various 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 (EPRI 2016).

VSP's principal purpose is to address the two main questions in sample planning: 1) how many samples are needed and 2) where should samples be taken? In addition to answering these questions, VSP can also generate sample plans for a multitude of different objectives, compare average concentration to a fixed threshold, locate hot spots, discover acceptable areas with high confidence, and detect trends. Figure B.2 below demonstrates these capabilities with a depiction of VSP's inverse square weighting interpolation of an Ac-228 hotspot.

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. Regarding interpolation, VSP uses simple or ordinary kriging. Unlike SADA, VSP does not implement co-kriging. Post-processing capabilities of VSP include the ability to generate maps of the kriging estimate, kriging variance, percentiles, interquartile range, or probability of exceeding a concentration threshold (EPRI 2016).

VSP is currently limited to two dimensions, although plans are to extend VSP capabilities to 3D. Additionally, a 3D approximation may be achieved through the projection of a search area onto the surface with indicated coring locations and depths. 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 exhibit a high degree of vertical anisotropy 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.

Like SADA, VSP cannot perform calculations of contaminant transport in the optimization of sample design. Therefore, usage of VSP is best for contaminants that are immobile or moving slowly with respect to the time between remediation and sampling; when multiple rounds of sampling are conducted; and/or when modeling is able to capture changes that occur over time in the dynamic system.

VSP is supported and maintained and has been subjected to verification and validation studies. SADA is not currently supported or maintained. Table B.1 highlights other differences between these two software packages.

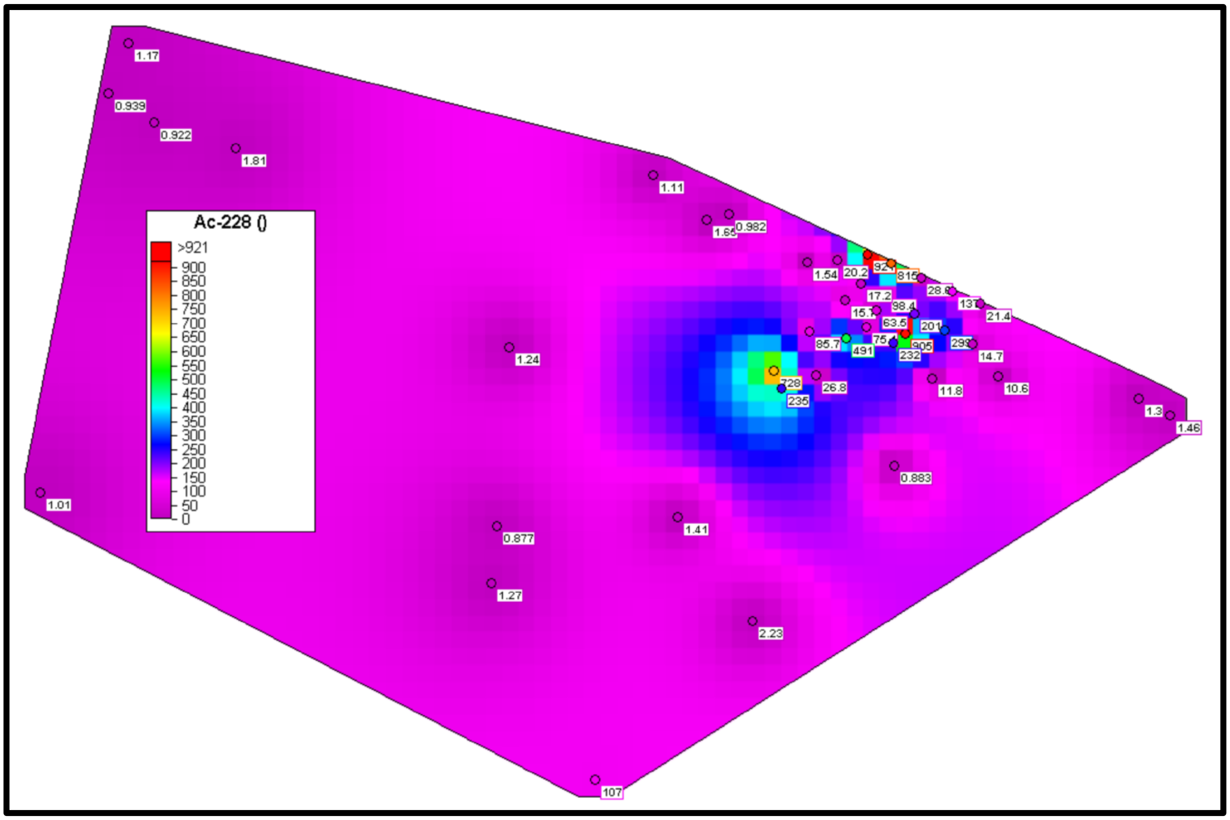

Figure B.2 VSP Inverse Square Weighting for Ac-228. Image Credit: Figure L-15, "Guidance on Surveys for Subsurface Radiological Contaminants" (SC&A 2022).

Table B.1 Comparison of SADA and VSP Features (SC&A White Paper 2022)

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

As discussed in Section A.5.2 above, the NRC is considering the recommendations in the PNNL Subsurface Scoping Report on tools to be added to VSP and is currently extending VSP to three dimensions and considering anisotropy in variogram fitting. Additional tools are expected to be prioritized and incorporated into the VSP computer code during the 2024 to 2028 timeframe in conjunction with development of an updated methodology in a revision to NUREG/CR-7021. Additionally, tools to facilitate importation, processing, and visualization of continuously collected data without audible surveyor vigilance is also being considered under contract with PNNL.

B.4 Other Data Visualization and Analysis Software

Two other applications evaluated in the EPRI (2016) report discussed in Section A.5.1 are C Tech Development Corporation's Earth Volumetric Studio and ESRI's[21] Geostatistical Analyst extension to their ArcGIS software. Both applications have a significant set of geostatistical analysis and data visualization tools along with other capabilities.

Earth Volumetric Studio offers various 2D and 3D kriging options, plus radial basis functions, inverse distance weighting, and natural neighbor interpolation methods. It integrates with common groundwater modeling software such as Groundwater Modeling System (GMS) and Groundwater Vistas, as well as ArcGIS and AutoCAD GIS software. It can account for anisotropy and assess model uncertainty and confidence. It also includes built in geologic layer modeling.

The ArcGIS Geostatistical Analyst extension offers a variety of 2D exploratory data analysis tools which are fully integrated with their industry standard GIS capabilities. These tools include data transformation options, outlier and hot spot analysis, tests for preferential sampling, and trend analysis and removal. These tools can be useful for pre-processing of data prior to importation and use in other geostatistical software or prior to use in Geostatistical Analyst with

[21] ESRI is a geographic information system company.

its deterministic and geostatistical interpolation methods. The software also has utilities to perform model validation and cross-validation, and geostatistical simulations.

APPENDIX C

SUBSURFACE SURVEY DESIGN OPTIMIZATION

C.1 Introduction

This chapter describes geostatistical methods for subsurface survey data analysis including methods to optimize subsurface sampling. Geostatistical methods enable inference and simulation of spatially referenced variables based on known observations from a set of sample locations. Additional tools are being considered for incorporation into the VSP as described in Sections 1.6.2 and 2.2.

C.2 Geostatistical Methods for Survey Design Optimization

Geostatistical methods can be used to estimate parameters or interpolate data values to support survey design and optimization. These methods leverage the stochastic nature of radiological contamination and cleanup using probability distribution functions or cumulative distribution functions (CDF) of parameters of interest. Unlike deterministic approaches, which produce a single parameter value, geostatistical models recognize a range of plausible values (e.g., concentrations, activity levels, etc.). For example, geostatistical maps are often produced by statistically selecting a representative value from a given CDF.

Cokriging and Markov Bayes are examples of geostatistical methods and are summarized below in sections 3.1.1 and 3.1.2, respectively. Other geostatistical methods include generalized least squares regression (GLS), local indicator of spatial association (LISA), and variogram tomography. GLS is a method used to estimate linear regression model parameters in the presence of spatial or temporal autocorrelation, accounting for spatial structures by incorporating them into the covariance matrix via a variogram. It has the flexibility to capture different spatial structures across layers or a grouping variable and can be used for mean estimation, prediction and interpolation, and hypothesis testing—making it a suitable method for subsurface investigations. The LISA method can be used to identify local clusters and spatial outliers and can be applied in 2-D surface and 3-D subsurface applications to discover hot spot areas or volumes. When nonlinear contamination pattern exist and anisotropy cannot be assumed to be stationary within the complex geological environments, variogram tomography should be considered. Solutions include incorporating locally varying anisotropy, kriging with external drift, and utilizing variogram matrix functions for vector random files.

Emerging artificial intelligence and machine learning techniques can be used to support these established methods. One of the reasons for the popularity of AI/ML methods is their flexibility to discover and model complex and nonlinear relationships in massive datasets, which could be used to predict contaminant levels at unmeasured locations by combining concentration samples with other subsurface measurements or models including groundwater transport, soil property, geophysical layers models. Few shot learning is a promising method in the absence of "big data," similar to what we might expect given few and costly subsurface sample data points. A more detailed description of all these geostatistical methods can be found in PNNL (2022).

C.2.1 Cokriging

Cokriging is a geostatistical method that exploits the relationships between different spatially distributed variables to refine overall prediction. This technique may be used to assess multiple radionuclides in parallel, to integrate various forms of data with varying accuracy into a single model, or to augment sparse measurements of a radionuclide of interest with a surrogate variable. In addition, cokriging may be used to incorporate different sources of data. For example, cokriging could enable the integration of surrogate variables such as measurements attained in counts per second. Cokriging may also be used to assess different radionuclides together to incorporate any interdependency (EPRI 2016).

There should either be empirical or physical rationale for using cokriging. Cokriging can be used for co-located measurements (e.g., Co-60 and Cs-137 concentration measurements at each sample location) or for instances in which a surrogate variable is available at many more locations than the primary variable of interest. Cokriging starts with structural analysis. The structural analysis required in cokriging is more demanding than in kriging because a variogram is required for each of the given regionalized variables and a cross-variogram is required for each pair of regionalized variables (EPRI 2016).

C.2.2 Markov Bayes

Markov Bayes method is derived from the Markov Model of coregionalization. The Markov Model is the most straightforward model of coregionalization with only one direct variogram needing to be modeled and with the other variograms derived through a proportional relationship. The Markov Model is used in the framework of collocated cokriging, which does not require knowledge of the variogram of the secondary variable since only one secondary datum is used for interpolation (SADA User Guide).

For the Markov Bayes geostatistical method, the earlier Markov model is modified for probability mapping using both hard data (measurements) and soft (prior probabilities) indicators. The model is then used to estimate the variogram between these two data sets to measure the correlation of the measured data and the prior beliefs. Hard data at unobserved locations is then predicted with cokriging. The advantage of this method is that it can be used to estimate the probability of any estimate exceeding a given threshold. A disadvantage of this method is the lack of uncertainty estimates associated with the posterior probabilities.

C.3 Subsurface Case Study Using Geostatistics (Fontenay-aux-Roses)

To provide examples of potential application of geostatistical tools to subsurface problems, a case study is provided below. This case and other case studies yet to be developed will be considered in developing guidance as discussed in Section A.5.

The subsurface characterization of the Fontenay-aux-Roses facility provides an example of cokriging. Fontenay-aux-Roses is a research facility in France that had subsurface contamination of Cs-137. A cokriging geostatistical method used hard data from a 2007 drill hole campaign to inform later drill hole campaigns in 2009 and 2010. The objective was to bound the horizontal extent of the contamination and to sample areas with the highest uncertainty. The figures below depict the map of borehole locations at the site and a 3D kriging map superimposed on the boreholes.

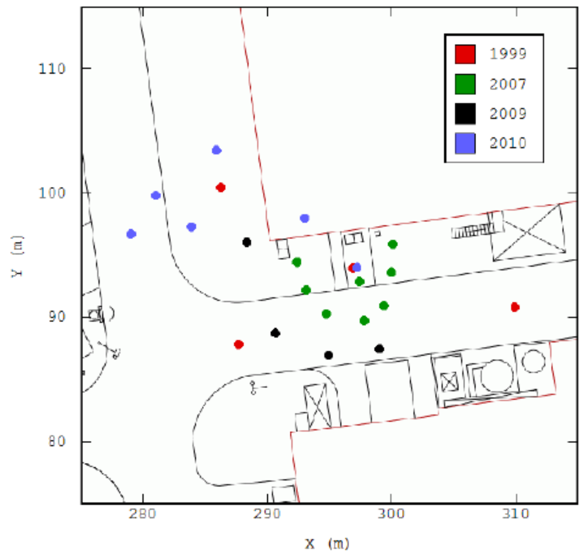

Figure C.1: Base Map of Drill Hole Campaigns. Image Credit: Figure 4-9, "Guidance for Using Geostatistics in Development a Site Final Status Survey Program for Plant Decommissioning," EPRI Report No. 3002007554 (2016).

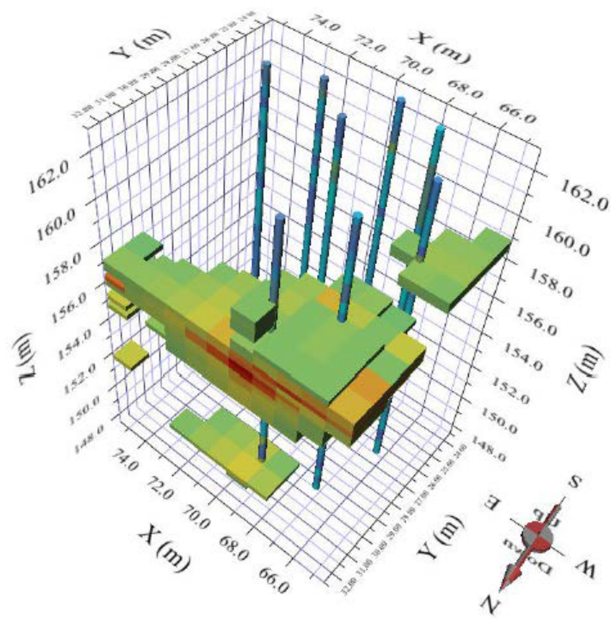

Figure C.2: Preliminary 3D Kriging Map of Cs-137 Concentrations. Image Credit: Figure 4-10, "Guidance for Using Geostatistics in Development a Site Final Status Survey Program for Plant Decommissioning," EPRI Report No. 3002007554 (2016).

At this site, cokriging revealed the existence of a thin contaminated layer along a vertical gradient. This geostatistical assessment was consistent with the known topology of an earlier site configuration involving a moat. This match led investigators to postulate that the contamination source was an accidental spillage from the storage pools or contaminated media used to fill the moat. The geostatistical modeling was later updated and refined using: 1) normal-score transformations of the data to reflect a normal distribution, 2) anisotropic variograms, and 3) conditional simulation to generate a map of probability exceeding an activity threshold “10 times greater than the highest detection limit for Cs-137” (EPRI 2016).

C.4 Artificial Intelligence/Machine Learning (AI/ML)

Subsurface data is typically obtained using measurements from borehole samples; however, use of borehole data may not be representative of the larger system and/or may only represent a single point in time in a dynamic system. To improve characterization while minimizing costs and exposure risk, few shot ML is being advanced in conjunction with remote subsurface sensing techniques to support high-performance forward prediction. This approach is being developed to reliably estimate the subsurface property distributions, including (but not limited to) permeability, porosity, and hydraulic conductivity, that control fate and transport of radioactivity in the environment, thereby addressing the scarcity of characterization data and complexities of heterogeneous subsurface systems. Further, applying ML approaches to a combination of discrete well or borehole datasets with modeled or surrogate data (i.e., output from flow and transport models, indirect measurements collected through ERT, spectral induced polarization, etc.), may lead to predictive models that capture relationships between different measurement methods and variables of interest that can be used for optimizing survey design or demonstrating compliance with release criteria. Meta learning algorithms and few shot learning are promising methods that could also be extended to automated variogram model fitting using training data from simulated and real data from various sites to facilitate geospatial modeling at sites with sparse data. Research to evaluate the potential for AI/ML to facilitate geostatistical analyses and reduce the need for highly trained experts is being considered as a longer-term activity.