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NUREG-2175

Guidance for Conducting Technical Analyses for 10 CFR Part 61

Draft Report for Comment

Office of Nuclear Material Safety and Safeguards

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ABSTRACT

This document provides guidance on conducting technical analyses (i.e., performance assessment, inadvertent intruder assessment, assessment of the stability of a low-level waste disposal site, defense-in-depth analyses, protective assurance period analyses, and performance period analyses) to demonstrate compliance with the performance objectives in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste." This document provides implementing guidance for amendments to 10 CFR Part 61 that are detailed in the proposed rule, "Low-Level Radioactive Waste Disposal," published in the *Federal Register* in 2015. As a result, this document is written as if the amendments to 10 CFR Part 61 in the cited proposed rule have been enacted; this document will be revised, if necessary, if the proposed rule is finalized. The guidance in this document is intended to supplement existing low-level radioactive waste guidance on issues pertinent to conducting technical analyses to demonstrate compliance with the performance objectives. This document provides detailed guidance in new areas that are less covered in existing guidance, such as the inadvertent intruder analysis, defense-in depth analyses, and analyses for the three phases of the analysis timeframe (compliance period, protective assurance period, and performance period). This guidance discusses the use of a graded level of effort needed to risk-inform the analyses for the compliance period (1,000 years), the protective assurance period (from 1,000 years to 10,000 years after disposal site closure), and also covers the performance period analyses that should be performed for analysis of long-lived waste beyond 10,000 years.

This guidance should facilitate licensees' implementation of the proposed amendments as well as assist regulatory authorities in reviewing the technical analyses. This guidance applies to all waste streams disposed of at a 10 CFR Part 61 low-level waste disposal facility, including large quantities of depleted uranium and blended waste. Additional topics covered in this document include (1) demonstration that radiation doses are minimized to the extent reasonably achievable; (2) the identification and screening of the features, events, and processes to develop scenarios for technical analyses; (3) the use of the waste classification tables or the results of the technical analyses to develop site-specific waste acceptance criteria; and (4) the use of performance confirmation to evaluate and verify the accuracy of information used to demonstrate compliance prior to site closure.

PREFACE

The U.S. Nuclear Regulatory Commission published the rulemaking, “Low-Level Radioactive Waste Disposal,” in 2015 (NRC, 2015a). This rulemaking includes detailed requirements for 10 CFR Part 61 licensees for performing technical analyses to demonstrate compliance with the performance objectives of Subpart C (i.e., 10 CFR 61.41 through 10 CFR 61.44). The purpose of this guidance document is to provide licensees with the tools to develop high-quality technical analyses, specifically the performance assessment, inadvertent intrusion assessment, site stability analyses, defense-in-depth analyses, protective assurance period analyses, and performance period analyses. This document should also be used by NRC or Agreement State regulators to identify risk-significant aspects of these technical analyses that should drive their review and decision-making process for the disposal site. This document refers to the reviewing authority as “NRC” or “NRC staff”, but these terms should be interpreted to mean Agreement State regulators as well, if applicable.

In addition to the technical analyses, this document covers the process for demonstrating compliance with 10 CFR 61.58, for waste acceptance. Licensees and reviewers may use this document to assist in developing the waste acceptance criteria for their disposal sites, as well as for developing acceptable processes for waste characterization and certification.

This document is written as if the amendments in the proposed rule have been enacted. However, for ease of reference, Appendix A highlights changes to 10 CFR Part 61 that were proposed in 2015 that identify new requirements, particularly relating to technical analyses and waste acceptance criteria.

This document is intended to provide guidance in a non-prescriptive manner; providing reference material for licensees, yet allowing flexibility for adapting this guidance to the specifics for each low-level waste disposal site. Additional details and examples are provided in appendices to this document, such as (1) hazard maps in Appendix B that may assist licensees and reviewers in determining site suitability, and (2) lists of example features, events, and processes in Appendix C that may assist licensees in defining the scope of the technical analyses. A glossary is provided in Section 13.0 that defines many of the terms used in this document.

To develop a succinct document, the NRC staff has written this guidance with the assumption that the reader has some level of proficiency in conducting technical analyses. For example, the NRC staff describes the application of model support and model abstraction for the performance assessment and intruder assessment and references existing documents for background information on these terms. Therefore, the NRC staff recommends that the reader become familiar with documents such as NUREG-1573, “A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities,” issued in October 2000 (NRC, 2000a), and other guidance documents referenced in Section 1.2, as background for this document.

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ACRONYMS AND ABBREVIATIONS

ACAP	Alternative Cover Assessment Project
ADAMS	Agencywide Documents Access and Management System
ALARA	as low as reasonably achievable
ASTM	American Society for Testing and Materials
BTP	branch technical position
BTP CA	BTP on concentration averaging and encapsulation
CFR	*Code of Federal Regulations*
CSDMS	Community Surface Dynamics Modeling System
DOE	U.S. Department of Energy
DQO	data quality objective
DU	depleted uranium
EPA	U.S. Environmental Protection Agency
ET	evapotranspiration
FEPs	features, events, and processes
FGR	Federal Guidance Report
FR	*Federal Register*
GIS	Geographic Information Systems
HLW	high-level waste
ICRP	International Commission on Radiological Protection
IMPEP	Integrated Materials Performance Evaluation Program
K_d	distribution coefficient
LLW	low-level radioactive waste
m	meter
mm	millimeter
mrem	millirem
mSv	millisievert
nCi/g	nanocuries per gram
NCRP	National Council on Radiation Protection and Measurements
NPV	net present value
NRC	U.S. Nuclear Regulatory Commission
OMB	Office of Management and Budget
PA	performance assessment
PAP	protective assurance period
PMF	probable maximum flood
PMP	probable maximum precipitation
PRA	probabilistic risk assessment
SOF	sum of fractions
QA	quality assurance
QA/QC	quality assurance/quality control
USGS	U.S. Geological Survey
yr	year

In this document, the first use of a technical term that is defined in the glossary is shown in *italics*.

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) establishes licensing requirements, performance objectives, and technical criteria for the *disposal* of commercial *low-level radioactive waste* (LLW) in *near-surface disposal facilities*. These requirements can be found in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 61, “Licensing Requirements for Land Disposal of Radioactive Waste” (NRC, 1982a; 47 FR 57446). This guidance document is intended to support the implementation of the requirements for *technical analyses* and waste acceptance to demonstrate compliance with the 10 CFR Part 61 performance objectives. This guidance supplements, rather than replaces, previous guidance. This document applies to all *waste streams* disposed at a 10 CFR Part 61 disposal facility, while providing specific considerations for long-lived and blended wastes (see Section 1.2.2), where appropriate.

1.1 Background

The regulations in 10 CFR Part 61 applies to any near-surface LLW disposal facility licensed after January 27, 1983. An integrated systems approach is emphasized in 10 CFR Part 61 for the disposal of commercial LLW, including site selection, disposal facility design and operation, minimum *wasteform* requirements, and disposal facility closure. To lessen the burden on society over the long periods of time contemplated for the control of the radioactive material and thus lessen reliance on *institutional controls*, 10 CFR Part 61 emphasizes passive, rather than active, systems to limit and retard radioactive releases to the environment.

To grant a license, the NRC (or Agreement State regulator) must conclude that there is reasonable assurance that the performance objectives of Subpart C will be met. To demonstrate that they will meet the performance objectives, 10 CFR Part 61 license applicants need to prepare several technical analyses. The technical analyses required for *licensees* to demonstrate that the performance objectives will be met are specified in 10 CFR 61.13.

Licensees must also meet specific technical requirements to ensure safe disposal of LLW. These requirements are specified in Subpart D and include, among others, requirements for waste acceptance that are specified in 10 CFR 61.58. The waste acceptance requirements are intended to ensure that the waste that licensees accept for disposal together with the *disposal site* and facility design provides reasonable assurance that the performance objectives of Subpart C will be met.

The regulatory requirements in 10 CFR Part 61 ensure public health and safety are protected during the operation of any commercial LLW disposal facility. 10 CFR Part 61 is performance-based and the technical criteria are written in relatively general terms, which allow applicants to demonstrate how their proposals meet the respective performance objectives for the specific near-surface disposal method selected. 10 CFR 61.7 identifies the overall philosophy and concepts that underlie the regulatory requirements of 10 CFR Part 61.

1.1.1 Performance Objectives

The performance objectives for a LLW disposal facility are contained in 10 CFR Part 61, Subpart C. The general requirement in 10 CFR 61.40 notes that land disposal facilities must be sited, designed, operated, closed, and controlled after closure so that reasonable assurance exists that exposures to humans are within the limits established in the performance objectives in 10 CFR 61.41 through 10 CFR 61.44. During and after facility operations, the performance objective at 10 CFR 61.41 requires the protection of the general population from releases of radioactivity.

- The performance objective 10 CFR 61.41(a) provides an annual *dose* limit of 0.25 milliSievert (mSv) [25 millirem (mrem)] for the *compliance period* and a requirement to limit releases to as low as reasonable achievable (ALARA).
- The performance objective in 10 CFR 61.41(b) requires concentrations of radioactive material that may be released to the general environment in groundwater, surface water, air, soil, plants, or animals shall be minimized during the *protective assurance period*, and that the annual dose shall be below 5 mSv (500 mrem) or a level that is supported as reasonably achievable based on technological and economic considerations.
- The performance objective in 10 CFR 61.41(c) requires releases of radioactivity from a disposal facility to the general environment at any time during the *performance period* to be minimized to the extent reasonably achievable.

The performance objective in 10 CFR 61.42 requires that the disposal facility must protect the *inadvertent intruder* at all times during the compliance period after active institutional controls are removed (i.e., 100 years after facility closure).

- The performance objective 10 CFR 61.42(a) provides an annual dose limit of 5 mSv (500 mrem) for the compliance period.
- The performance objective in 10 CFR 61.42(b) requires that design, operation, and closure of the *land disposal facility* shall minimize exposures to any inadvertent intruder into the disposal site at any time during the protective assurance period and that the annual dose shall be below 5 mSv (500 mrem) or a level that is supported as reasonably achievable based on technological and economic considerations.
- The performance objective in 10 CFR 61.42(c) requires exposures to the inadvertent intruder at any time during the performance period to be minimized to the extent reasonably achievable.

Sections 10 CFR 61.41 and 10 CFR 61.42 require a demonstration of protection beyond closure of the disposal facility. The length of time that these requirements specify is defined in 10 CFR 61.2, "Definitions". Specifically:

> *Compliance period* is the time out to 1,000 years after closure of the disposal facility.
>
> *Protective assurance period* is the period from the end of the compliance period through 10,000 years following closure of the site.
>
> *Performance period* is the timeframe established for considering waste and site characteristics to evaluate the performance of the site after the protective assurance period.

The performance objective in 10 CFR 61.43 requires protection of individuals during operations. Compliance with 10 CFR 61.43 is determined largely through compliance with the standards for radiation protection set forth in 10 CFR Part 20, and therefore, is not discussed further in this document.

The performance objective set forth in 10 CFR 61.44 requires that the licensee demonstrate that the disposal facility will be sited, designed, used, operated, and closed to achieve long-term *stability* of the disposal site for the compliance and protective assurance periods. Long-term stability of the disposal site eliminates, to the extent practicable, the need for ongoing active maintenance of the disposal site following closure so that only surveillance, monitoring, or minor custodial care is required.

1.1.2 Safety Case

Section 10 CFR 61.2 defines a *safety case* as a collection of information that demonstrates the assessment of the safety of a waste disposal facility. This includes the technical analyses discussed in Section 1.1.4, as well as information on defense-in-depth and supporting evidence and reasoning on the strength and reliability of the technical analyses and the assumptions made therein. The safety case also includes description of the safety relevant aspects of the site, the design of the facility, and the managerial control measures and regulatory controls.

A safety case for a land disposal facility covers the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility. The purpose of a safety case is to provide a sufficient level of detail regarding the description of all safety relevant aspects of the site, the design of the facility, and the managerial control measures and regulatory controls to inform the decision whether to grant a license for the disposal of LLW and provide the public assurance that the facility will be designed, constructed, operated, and closed safely (IAEA, 2012).

Licensing decisions are based on whether there is reasonable assurance that the performance objectives can be met. Defense-in-depth protections, such as siting, wasteforms, radiological source-term, engineered features, and natural system features of the disposal site, combined with technical analyses and scientific judgment form the safety case for licensing a LLW disposal facility. The insights derived from technical analyses include supporting evidence and reasoning on the strength and reliability of the layers of defense relied upon in the safety case. These insights provide input for making regulatory decisions. The safety case must conclude that public health and safety will be adequately protected from the disposal of LLW (including long-lived LLW). A clear case for the safety of a disposal facility also serves to enhance the communication among stakeholders.

Finally, the NRC staff envisions that the safety case for a land disposal facility would evolve over time as new information is gained during the various phases of the facility's development and operation. Therefore, the NRC staff expects that the safety case will be updated as new information that could significantly impact safety of the facility is learned. Section 10 CFR 61.28(a) requires that the application for closure of a licensed land disposal facility must include a final revision to the safety case.

1.1.3 Defense-in-Depth Analyses

Section 10 CFR 61.2 defines defense-in-depth as the use of multiple independent and redundant layers of defense such that no single layer, no matter how robust, is exclusively relied upon. Defense-in-depth for a land disposal facility includes, but is not limited to, the use of siting, wasteforms and radionuclide content, engineered features, and natural geologic features of the disposal site. Section 8.0 describes the information that a licensee should provide and a *reviewer* should evaluate with respect to the technical analyses for demonstrating that a land disposal facility incorporates defense-in-depth protections during the operational and post-closure phases of the land disposal facility lifecycle. Section 10 CFR 61.13(f) requires licensees to complete analyses that demonstrate the proposed disposal facility includes defense-in-depth protections.

1.1.4 Technical Analyses

The technical analyses needed to demonstrate that the performance objectives of Subpart C are met are provided in 10 CFR 61.13(a) through (f). Technical analyses assess the impact of site-specific factors on the performance of the disposal facility and the site environment both (1) during the operational period, as in the analysis for protection of individuals during operations, and (2) for disposal of radioactive waste over the longer term, as in the analyses for protection of the general population from releases of radioactivity, protection of inadvertent intruders, stability of the disposal site after closure, and assessment of long-term impacts from LLW disposal over the protective assurance and performance periods.

In this document, the term "technical analyses" comprises the *performance assessment*, *intruder assessment*, *site stability analysis*, *defense-in-depth* analyses, protective assurance period analyses, and *performance period analyses*. A description of each of the analyses is presented in the following sections.

1.1.4.1 *Performance Assessment*

A performance assessment (PA) is a type of *risk* analysis that addresses (1) what can happen, (2) how likely it is to happen, and (3) what are the resulting impacts (Eisenberg et al, 1999). These impacts can then be compared to the performance objective in 10 CFR 61.41 (radiological protection of the general public). The requirements for a performance assessment are set forth in 10 CFR 61.13(a). A performance assessment shall:

(1) Consider features, *events*, and processes (*FEP*s) that might affect demonstration of compliance with 10 CFR 61.41. The FEPs considered must represent a range of phenomena with both beneficial and adverse effects on performance, and must consider the specific technical information required in 10 CFR 61.12(a) through 10 CFR 61.12(i). A technical basis for inclusion or exclusion of specific FEPs must be provided.

(2) Evaluate specific FEPs if their omission would significantly affect meeting the performance objective specified in 10 CFR 61.41.

(3) Consider the likelihood of disruptive or other unlikely FEPs for comparison with the limits set forth in 10 CFR 61.41.

(4) Reflect new FEPs different from the compliance period that address significant uncertainties inherent in the long timeframes associated with demonstrating compliance with 10 CFR 61.41(b) only if scientific information compelling such changes is available.

(5) Provide a technical basis for either inclusion or exclusion of *degradation*, deterioration, or alteration processes (e.g., of the *engineered barriers*, wasteform, site characteristics) and interactions between the disposal facility and site characteristics that might affect meeting the performance objective in 10 CFR 61.41.

(6) Provide a technical basis for *models* used in the performance assessment such as comparisons made with outputs of detailed process-level models or empirical observations (e.g., laboratory testing, field investigations, and natural analogs).

(7) Evaluate *pathways* including air, soil, groundwater, surface water, plant uptake, and exhumation by burrowing animals.

(8) Account for uncertainties and variability in the projected behavior of the disposal system (e.g., disposal facility, natural system, and environment).

(9) Consider *alternative conceptual models* of *features* and *processes* that are consistent with available data and current scientific understanding, and evaluate the effects that alternative conceptual models have on the understanding of the performance of the disposal facility.

(10) Identify and differentiate between the roles performed by the natural disposal site characteristics and design features of the disposal facility in limiting releases of radioactivity to the general population.

1.1.4.2 *Inadvertent Intrusion Assessment*

The 10 CFR Part 61 regulations envision a period of active institutional controls for 100 years following closure of the LLW disposal facility. During that time period, the disposal site and its contents are protected from disturbance by potential intruders through a series of measures (e.g., site access controls). At the end of the 100 years of active institutional controls, 10 CFR Part 61 requires licensees to assume there will be no active caretaking of the disposal site and it is possible for inadvertent intruders to gain access. An inadvertent intruder is defined in 10 CFR 61.2, "Definitions," as "a person who might occupy the disposal site after closure and engage in normal activities, such as agriculture, dwelling construction, resource exploration or exploitation (e.g., well drilling) or other reasonably foreseeable pursuits that might unknowingly expose the person to radiation from the waste included in or generated from a disposal facility." Licensees should demonstrate that potential inadvertent intruders, who might occupy the site at any time after institutional controls over the disposal site are removed, will be protected.

An inadvertent intrusion assessment (also referred to as an "intruder assessment") is an iterative process involving site-specific, prospective modeling evaluations of potential radiological consequences as a result of reasonably foreseeable human activities that might unknowingly occur should an individual occupy a near-surface facility for disposal of LLW after the loss of institutional controls. The intruder assessment is used to evaluate how these impacts compare to the performance objective in 10 CFR 61.42.

Because there is no scientific basis for quantitatively predicting the probability of a future disruptive human activity over long timeframes, an inadvertent intruder assessment does not consider the probability of inadvertent intrusion occurring. Rather, the assessment assumes that reasonably bounding *receptor scenarios* occur and evaluates the radiological consequences that could be experienced by inadvertent intruders should institutional controls or societal memory be lost (NCRP, 2005).
As stated in 10 CFR 61.13(b), analyses of the protection of inadvertent intruders must demonstrate there is reasonable assurance the *waste acceptance criteria* developed in accordance with 10 CFR 61.58 will be met, adequate barriers to inadvertent intrusion will be provided, and any inadvertent intruder will not be exposed to doses that exceed the limits set

forth in 10 CFR 61.42 as demonstrated in an intruder assessment. An intruder assessment shall:

(1) Assume that an inadvertent intruder occupies the disposal site at any time during the compliance period (i.e., 1,000 years) after the period of institutional controls ends, and engages in normal activities including agriculture, dwelling construction, resource exploration or exploitation (e.g., well drilling), or other reasonably foreseeable pursuits that are consistent with activities in and around the site at the time of closure and that unknowingly expose the intruder to radiation from the waste.

(2) Identify adequate barriers to inadvertent intrusion that inhibit contact with the waste or limit exposure to radiation from the waste, and provide a basis for the time period over which barriers are effective.

(3) Account for uncertainties and variability.

1.1.4.3 ***Site Stability Analysis***

The site stability analysis evaluates the long-term stability of the disposal site and can be used by a licensee to determine compliance with 10 CFR 61.44 (see Section 5.0). The specific requirements for the analyses are set forth in 10 CFR 61.13(d):

> Analyses of the long-term stability of the disposal site and the need for ongoing active maintenance after closure must be based upon analyses of active natural processes, such as erosion, mass wasting, slope failure, settlement of wastes and backfill, infiltration through covers over disposal areas and adjacent soils, and surface drainage of the disposal site. The analyses must provide reasonable assurance that long-term stability of the disposal site can be ensured and that there will not be a need for ongoing active maintenance of the disposal site following closure.

1.1.4.4 ***Protective Assurance Period Analyses***

The primary purpose of the protective assurance period analyses is to provide information that demonstrates that releases of radioactivity from a LLW disposal facility are minimized during the protective assurance period, which is the period from the end of the compliance period through 10,000 years following closure of the site. Minimization is the reduction of doses to as low as reasonably practical with technical and economic factors taken into consideration. The performance objectives in 10 CFR 61.41(b) and 10 CFR 61.42(b) require that the annual dose shall be below 5 mSv (500 mrem) or a level that is supported as reasonably achievable based on technological and economic considerations for (1) concentrations of radioactive material that may be released to the general environment, and for (2) exposures to any inadvertent intruder, respectively. Section 6.0 provides guidance on developing the technical analyses for the protective assurance period.

1.1.4.5 ***Performance Period Analyses***

The primary purpose of the performance period analyses is to provide information to decision-makers with respect to the potential performance of the disposal site for the disposal of *long-lived waste*. Licensees should conduct performance period analyses for the period after the 10,000 year (yr) protective assurance period. Performance period analyses are not required if the disposal facility is not accepting sufficient quantities of long-lived waste. Section 7.0

provides guidance on how to determine if performance period analyses are necessary. The performance period analyses are only required for disposal sites with waste that contains radionuclides with average concentrations exceeding the values specified in Table A of 10 CFR 61.13(e), or if necessitated by site-specific conditions. The performance period analyses required at 10 CFR 61.13(e) shall:

(1) Assess how the disposal site limits the potential long-term radiological impacts, consistent with available data and current scientific understanding.

(2) Identify and describe the features of the design and site characteristics that will demonstrate that the performance objectives set forth in 10 CFR 61.41(c) and 10 CFR 61.42(c) will be met.

The analyses must indicate the long-term performance of the land disposal facility and effort shall be made to minimize releases of radioactivity from a disposal facility to the general environment to the extent reasonably achievable at any time during the performance period. The analyses for the performance period may be similar to the analyses performed for the compliance period and/or the protective assurance period, but they are not required to be the same.

Figure 1-1 provides the relationship of the major components of the technical analyses with respect to analysis timeframes and each other. For example, the *Assessment Context* and *Scenario Development* component applies to the performance assessment, intruder assessment, and site stability analyses (see Sections 2.3 and 2.5).

Both the performance assessment and intruder assessment are evaluated over all three timeframes, however, the stability analyses are only applied to the compliance period and protective assurance period. Defense-in-depth is applicable over all three time periods and all three analysis types. All of the information contributes to the demonstration that the Subpart C performance objectives are met.

1.1.5 Waste Acceptance Requirements

Requirements for waste acceptance are specified in 10 CFR 61.58, "Waste Acceptance". The regulations require licensees to identify (1) criteria for the acceptance of waste for disposal (i.e., waste acceptance criteria), (2) acceptable methods for characterizing the waste, and (3) a program to certify that waste meets the acceptance criteria prior to transfer to the disposal facility. The waste acceptance requirements are intended to provide reasonable assurance that the performance objectives of Subpart C will be met.

The waste acceptance criteria, as specified in 10 CFR 61.58(a) must identify allowable activities and concentrations of specific radionuclides, acceptable wasteform characteristics and container specifications, and restrictions or prohibitions on waste, materials, or containers that might affect meeting the performance objectives. The criteria for allowable activities and concentrations of specific radionuclides must be developed from either the technical analyses required by 10 CFR 61.13 for any land disposal facility or the waste classification requirements set forth in 10 CFR 61.55 for a near-surface disposal facility.

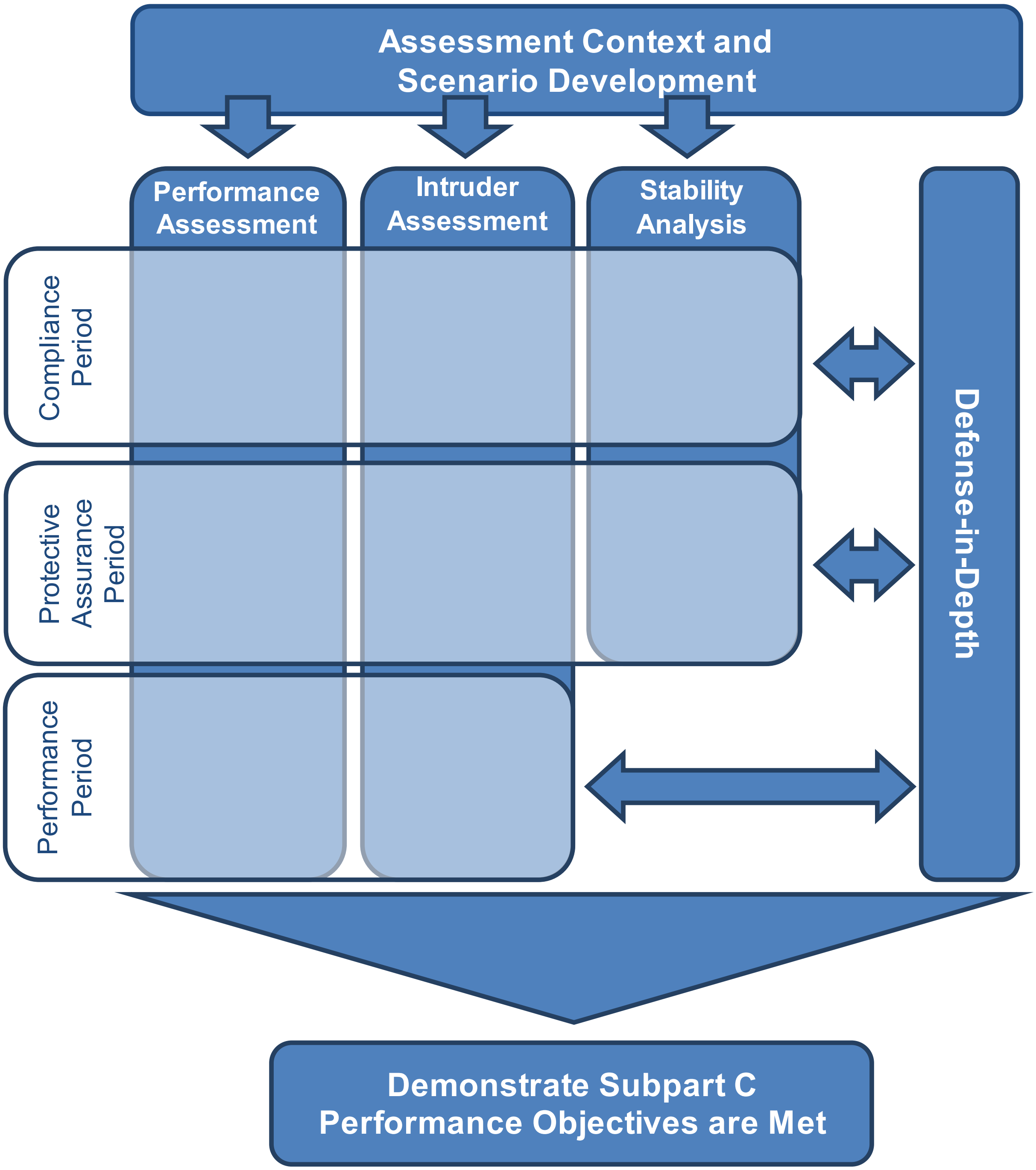

Figure 1-1 Technical Analyses Relationship to Analyses Timeframes and Performance Objectives

Licensees must also identify acceptable methods for characterizing the waste for acceptance. The regulations in 10 CFR 61.58(b) specify the minimum information that the acceptable methods must include to adequately characterize waste for acceptance. The intent of these requirements is to ensure that knowledge of the waste's characteristics is commensurate with the assumptions and approaches employed in the technical analyses used to develop the waste acceptance criteria and is, thus, sufficient to demonstrate that the waste acceptance criteria are met.

10 CFR 61.58(c) requires a program to certify that waste meets the acceptance criteria prior to shipment to the disposal facility. Certification of waste provides assurance that a disposal facility operates within the limits established to demonstrate compliance with the performance objectives of Subpart C. The certification program must:

(1) Designate authority to certify and receive waste for disposal.

(2) Provide procedures for certifying that waste meets the waste acceptance criteria.

(3) Specify documentation required for waste characterization, shipment, and certification.

(4) Identify records, reports, tests, and inspections that are necessary.

(5) Provide approaches for managing waste to maintain its certification status.

Finally, 10 CFR 61.58(f) requires that each licensee shall annually review the content and implementation of the waste acceptance criteria, waste characterization methods, and certification program.

1.1.6 Agreement State Interactions

Agreement State regulators may request technical assistance from the NRC staff to conduct reviews of the technical analyses listed above and also to assist in interpreting the guidance in this document. NRC provides three types of technical assistance to Agreement States: routine, special, and programmatic (NRC, 2013).

Routine technical assistance is provided as part of NRC's daily interaction with Agreement States. This assistance may include, but is not limited to, the discussion of technical issues regarding licensing, compliance, and security. Examples of routine technical assistance include requests for and the sharing of information on licensing, inspection, security, and enforcement activities. The NRC staff may perform confirmatory reviews of portions of completed Agreement State technical assessments, on a case-by-case basis, when resources are available.

Special technical assistance may require specific assignment of the NRC staff or consultants for a specified period and for a specific job. An Agreement State may not have the special technical expertise that is required to address a particular need, or an Agreement State may experience a temporary constraint on resources. Consequently, an Agreement State may request direct special technical assistance from NRC that would involve NRC licensing and inspection staff conducting independent licensing. Direct technical assistance to an Agreement State in these circumstances will be conducted on a case-by-case basis when NRC believes that such assistance is necessary. The provision of such assistance will be based on the availability of staff resources and any assistance will be cost-reimbursable.

Programmatic technical assistance is addressed as part of the Integrated Materials Performance Evaluation Program (IMPEP) process. See Management Directive 5.7 “Technical Assistance to Agreement States” for additional details on requesting technical assistance from the NRC staff (NRC, 2013).

1.2 Purpose of This Guidance Document

This guidance document is intended to support the implementation of the requirements for technical analyses and waste acceptance to demonstrate compliance with the 10 CFR Part 61 performance objectives.

1.2.1 Relationship to Other NRC Guidance

The NRC staff has issued several guidance documents to assist in the implementation of the requirements of 10 CFR Part 61. Additionally, in certain cases, guidance for other NRC regulatory programs (e.g., NUREG-1757) may be adapted to 10 CFR Part 61. Early guidance for the implementation of 10 CFR Part 61 (e.g., NUREG-1199 and NUREG-1200) was generally prescriptive. More recently, review of site-specific performance assessments has become more performance-based, driven in part by the Commission’s 1995 probabilistic risk assessment (PRA) policy statement (NRC, 1995a). More recent guidance (e.g., NUREG-1573 and NUREG-1854) has been developed that might be helpful for completing or reviewing a performance assessment. The following documents, among others provided in Section 11.0 of this document, are available to 10 CFR Part 61 licensees and reviewers for guidance:

(1) NUREG-1200, Revision 3, “Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility,” issued April 1994, provides regulators with procedures and guidance for reviewing license applications for new disposal facilities (NRC, 1994). NUREG-1200 identifies areas of review and review procedures for evaluating technical analyses, including what is referred to today as a performance assessment (NRC, 1994). NUREG-1200 was developed using a regulatory approach that was generally prescriptive.

(2) NUREG-1573, “A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities” was issued in October 2000 to assist licensees in performing performance assessments to comply with 10 CFR 61.41 (NRC, 2000a) and is referenced throughout this document. NUREG-1573 developed a bibliography of technical references applicable to LLW disposal (as of 2000) in its Appendices B and C. NUREG-1573 provides guidance on an acceptable approach for systematically integrating *site characterization*, facility design, and performance modeling into a single performance assessment process for purposes of demonstrating compliance with 10 CFR 61.41. The guidance in NUREG-1573 might help ensure the consistency of different reviews.

In some cases, NUREG-1573 provides information on topics (e.g., analyses timeframes, climate) that is also covered in this guidance document. Information provided in this guidance document supersedes guidance in older documents that is inconsistent with the guidance in this document. The superseded guidance includes: consideration of site characteristics, timeframe for the analyses, current land use, analysis of engineered barrier performance, climate change, and consideration of disruptive events. 10 CFR

Part 61 has changed since NUREG-1573 was developed in 2000 (see Appendix A). In addition, different types of wastes (e.g., larger quantities of long-lived waste) are being considered for disposal. Therefore, this guidance also supplements the guidance in NUREG-1573.

(3) NUREG-1854, "NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations," issued August 2007, provides guidance specific to the NRC staff's review of technical analyses for DOE waste determinations (NRC, 2007a). DOE uses technical analyses that are documented in a "waste determination" to evaluate whether the waste at four sites in the States of South Carolina, Idaho, Washington, and New York, is high-level waste (HLW) or *waste incidental to reprocessing* (incidental waste). A waste determination is DOE's analysis of whether the waste will meet the applicable criteria to be classified as incidental waste. The four DOE sites are operating under different requirements for waste evaluation and management; however, they all include criteria that specifies the waste will be disposed of in compliance with, or with comparable safety requirements to, the performance objectives in 10 CFR Part 61, Subpart C. NUREG-1854 contains information that can also be used for conducting the technical analyses referred to in this document.

(4) "Final Branch Technical Position on Concentration Averaging and Encapsulation, Revision in Part to Waste Classification Technical Position," dated January 17, 1995 (NRC, 1995b), defines a subset of concentration averaging and encapsulation practices that the NRC staff finds acceptable in determining the concentrations of the radionuclides tabulated in 10 CFR 61.55, "Waste Classification." Although this branch technical position (BTP) is more intended to aid LLW generators in determining wasteform concentrations, it may prove useful to LLW disposal facility operators in determining site-specific waste acceptance criteria (see Section 9.0). The NRC staff updated this BTP and issued "Draft Branch Technical Position on Concentration Averaging and Encapsulation, Revision 1" in May 2012 that revised the NRC staff positions in the 1995 version (NRC, 2012a). The NRC staff expects to complete the final version of this BTP by the end of 2014.

(5) NUREG-1757, "Consolidated NMSS Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Criteria," dated September 30, 2006, provides guidance on the evaluation of engineered barriers used in site decommissioning (NRC, 2006). If similar engineered barriers are used in land disposal of LLW, then this guidance might be useful to a licensee.

The purpose of this guidance document is to complement the aforementioned documents and provide guidance in areas not previously covered. The NRC staff has attempted to provide references to other guidance documents that may be useful for specific topics. Section 11.0 of this document contains a road map directing the reader to individual sections of the documents above, as well as to other guidance documents that might be useful to 10 CFR Part 61 licensees and reviewers.

1.2.2 What is New in this Document?

A primary purpose of this document is to update guidance on conducting technical analyses to demonstrate compliance with the performance objectives of Subpart C. Several new areas discussed in this document are:

(1) Acceptable approaches to identify and screen FEPs to develop *scenarios*

(2) Detailed guidance on the analysis for the protection of the inadvertent intruder

(3) Detailed guidance and examples for conducting site stability analyses that evaluate the long-term stability of the disposal site and determines compliance with 10 CFR 61.44

(4) Development of waste acceptance criteria, waste characterization methods, and waste certification

(5) Risk-informing the analyses for the three-tiered analysis timeframe: the compliance period (1,000 years), the protective assurance period (from 1,000 to 10,000 years), and the performance period analyses (for long-lived waste beyond 10,000 years), using a graded level of effort

(6) Defense-in-depth analyses that demonstrate the proposed disposal facility includes defense-in-depth protections

(7) Discussion of a safety case as a collection of information that demonstrates the assessment of the safety of a waste disposal facility

(8) Performance confirmation and the conduct of periodic reviews for technical analyses and waste acceptance criteria

A disposal facility licensed under 10 CFR Part 61 must meet the performance objectives for all waste disposed of at the site. The technical analyses described in this document should be performed for the total inventory of waste at the site. As such, this document does not provide guidance specific to any particular waste. Rather, it provides guidance for the total waste inventory at each site. However, the NRC staff has attempted to provide examples in this guidance of the use of graded levels of effort required for the analyses of long-lived waste versus the analyses of conventional short-lived waste (e.g., long-lived waste often requires more complex technical analyses).

1.3 Document Organization

This document provides guidance on conducting technical analyses to demonstrate compliance with the performance objectives of 10 CFR Part 61. This guidance document discusses the parameters and assumptions that can be used in conducting these technical analyses in a broad sense, rather than in a prescriptive manner, to allow flexibility to licensees (see Example 1.1). The NRC staff considers this flexibility necessary because the site-specific nature of LLW disposal can make specification of particular models or parameter values impractical. Table 1-1 presents the technical analyses, the relevant requirements in 10 CFR Part 61, and the individual sections of this document where licensees and regulators can find guidance related to the analyses.

Table 1-1 Crosswalk between Technical Requirements and Document Sections

		Section Number								
Technical Requirement	**Rule Section**	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**9.0**
Performance Assessment	61.13(a) 61.41(a)	X	X	X						
Inadvertent Intrusion Assessment	61.13(b) 61.42(a)	X	X		X					
Site Stability Analysis	61.13(d) 61.44	X	X			X				
Protective Assurance Period Analysis	61.41(b) 61.42(b)	X	X				X			
Performance Period Analysis	61.13(e) 61.41(c) 61.42(c)	X	X					X		
Defense-in-Depth Analysis	61.13(f)	X							X	
Waste Acceptance	61.58	X								X

Example 1.1: How much detail is provided on parameters and assumptions that can be used in conducting technical analyses?

The NRC staff identifies methodologies for performance assessment and intruder assessment that licensees can use to demonstrate compliance with the 10 CFR Part 61 performance objectives. The guidance discusses important FEPs that should be evaluated as part of the scenario analysis process and considerations for abstracting the FEPs into computational models in the performance and intruder assessments. The NRC staff presents key FEPs in a broad sense to indicate the types of FEPs that should be considered based on experience with radioactive waste disposal facilities. For example, the guidance indicates that sorption should be considered in evaluating the migration of radionuclides in the environment rather than specifying a specific sorption model or parameter values that should be used. Licensees are encouraged to consult this guidance document to identify potential FEPs for a specific site; however, licensees should develop models and parameters to adequately represent their disposal site's performance consistent with the expected temporal behavior of the disposal system. This development might allow for consideration of a subset of the FEPs identified in this guidance document or might require the consideration of additional FEPs beyond those identified in this guidance.

Section 2.0 summarizes general considerations for conducting technical analyses, such as *model abstraction*, *model uncertainty*, and *model support*. Sections 2.0 and 3.0 provide guidance for specific topics related to performance assessment modeling concerned with radiological protection of the general public, as required in 10 CFR 61.41. Section 4.0 provides guidance specific to the analysis required for radiological protection of the inadvertent intruder, as required in 10 CFR 61.42. Section 5.0 provides guidance on stability of the disposal site after closure, as required in 10 CFR 61.44. Section 6.0 discusses the protective assurance period analysis and Section 7.0 provides guidance on the performance period analyses for 10 CFR 61.13(e) associated with the disposal of long-lived waste. Section 8.0 discusses the defense-in-depth analysis required under 10 CFR 61.13(f). Section 9.0 discusses the process for waste acceptance, such as developing waste acceptance criteria and performing waste characterization and waste certification. Section 10.0 discusses conducting performance confirmation to evaluate and verify the accuracy of information used to demonstrate compliance prior to site closure. Section 11.0 provides references for the use of other NRC guidance documents. Section 12.0 provides the references cited in this document and Section 13.0 contains a glossary of technical terms used in this guidance.

1.4 Risk-Informed Approach

This document should be implemented in a risk-informed manner. In NUREG-1614 (NRC, 2012b), risk-informed is defined as "an approach to decision-making in which risk insights are considered along with other factors such as engineering judgment, safety limits, and redundant and/or diverse safety systems. Such an approach is used to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety." (e.g., the risk to human health associated with exposure to ionizing radiation). A reviewer should place relatively more emphasis on technical information associated with systems that prevent a risk[1] from being realized or that significantly reduce the magnitude of a risk. Licensees should perform sufficient evaluation and develop adequate bases to identify and emphasize the key areas of the performance assessment, intruder assessment, and site stability evaluation that are expected to have the biggest impact on public health and safety. The type, quantity, and concentration of waste that a facility receives will drive the risk which in turn will drive the level of detail of the assessments.

Various sections of this document provide risk-informed guidance. Although conducting analyses for the compliance period and the protective assurance period requires projecting doses for up to 10,000 years, the scope, technical bases, and level of detail should be tailored to the waste characteristics. For example, the level of effort required for model support for the performance assessment to demonstrate compliance with 10 CFR 61.41 will most likely be higher than the level of effort that should be expended for the performance period analyses. More robust model support may be needed for the performance period analyses if large quantities and/or high concentrations of long-lived waste are present at the disposal site.

The approach to the intruder dose assessment described in Section 4.0 provides methods for risk-informing scenario selection by considering site environmental conditions and land use information. The analysis recommended for the site stability evaluation in Section 5.0 will ensure that the complexity of the evaluation is commensurate with the *hazard* of the material that will be disposed.

[1] Risk is a product of likelihood and consequence. Risk-informed review generally focuses on the probability-weighted consequences (i.e., the likelihood, the consequences, or both).

2.0 GENERAL TECHNICAL ANALYSES CONSIDERATIONS

The term “technical analyses” refers to the performance assessment, intruder assessment, site stability evaluation, and performance period analyses needed to demonstrate compliance with the 10 CFR Part 61 Subpart C performance objectives. Defense-in-depth analyses are discussed in Section 8.0. This section is intended to provide general guidance for preparing these four types of analyses, with emphasis on the performance assessment. The purpose of this document is to supplement existing NRC 10 CFR Part 61 guidance, such as the guidance found in NUREG-1199 (NRC, 1991a), and to present new guidance in areas not previously covered.

This section describes the information that a licensee should provide and a reviewer should evaluate with respect to the basic elements of technical analyses that typically comprise a performance assessment. Many of the basic elements of the technical analyses that apply to the performance assessment also apply to the intruder assessment, site stability assessment, and performance period analyses. For example, data adequacy, uncertainty, and model support are important with respect to the all of the technical analyses.

For efficiency purposes, the general information contained in Section 2.2 that is relevant to the other technical analyses that are discussed in later sections of this document (e.g., Section 4.0, 5.0, 6.0) is not replicated in those sections. Section 2.2 was written for preparation and review of performance assessments. Intruder assessments are generally more constrained assessments using stylized scenarios that involve calculation but do not typically involve development of integrated *conceptual models* (see Section 4.0). The guidance in Section 2.2 could be applicable to the site stability assessment if a model-based approach is used, but would be of limited applicability if a design-based approach is used (see Section 5.0). The performance period analyses discussed in Section 7.0 may be not required for disposal of certain short-lived wastes, therefore, the guidance in Section 2.2 has low applicability if only a screening analysis is performed, but has applicability if a quantitative probabilistic assessment is developed.

Other portions of this section of the guidance may also be applicable to the intruder assessment, stability assessment, or performance period analyses. To the extent possible, the NRC staff has noted in individual portions of the text where the material presented for preparation and review of a performance assessment is also applicable to the other technical analyses.

A technical analysis such as a performance assessment can be a collection of other models (e.g., submodels or process models) of varying levels of complexity, or it can be an integrated model. A submodel is a representation of a specific process as part of the technical analysis, such as a model estimating the rate of infiltration of water to the waste in a performance assessment. Technical elements that form the basic components of performance assessment modeling include *system description*, data adequacy, future uncertainty, model uncertainty, *parameter uncertainty*, model support, and integration. These technical elements, though integral to performance assessment, may also be applicable to the other technical analyses required by 10 CFR Part 61.

2.1 Assessment Process

Figure 2-1 provides the steps of the performance assessment process that may be used by licensees. Development of the assessment context is the first step in the performance assessment methodology followed by the description of the system (see Figure 2-1). After development of the system description, a licensee would complete scenario development. Scenario development includes the identification and categorization of FEPs, the screening of FEPs, and the representation of the screened FEPs in scenarios. These steps will vary slightly if the licensee uses a top-down approach to scenario development compared to a bottom-up approach, as described in Section 2.5. Based on the scenarios that result from scenario development, a licensee can develop conceptual models that are implemented as *numerical models*. As discussed in the following sections, licensees should account for uncertainty throughout the process. Future uncertainty is accounted for by developing and analyzing scenarios, or alternative future system states, and model uncertainty is accounted for by developing and analyzing conceptual models.

2.1.1 Terms and Definitions

Features, events, processes, scenarios, and other relevant terms used in this section are defined below. Section 13.0 presents a glossary of terms for the whole document.

Feature is an object, structure, or characteristic that has a potential to affect the performance of the disposal system. Examples include rocks within an erosion layer of an engineered cover or a drainage layer of an engineered cover.

Event is a qualitative or quantitative *phenomenon* or change that has the potential to affect the performance of the disposal system and that occurs during an interval that is short compared to the analyses timeframe. Examples of events that cause relative rapid change are earthquakes, floods, storms, well drilling, and excavation.

Process is a qualitative or quantitative phenomenon or change that has the potential to affect the performance of the disposal system and that occurs during all or a significant part of the analyses timeframe. Examples of processes that cause relative gradual change are radionuclide transport, differential settlement, leaching, and erosion.

FEP categorization is the process of organizing individual FEPs into categories of similar properties to facilitate FEP screening. For example, FEPs related to natural, human, or waste phenomena may be grouped into separate categories.

FEP screening is the process of using regulatory, probability, and consequence criteria to eliminate FEPs from further consideration that will not significantly impact the performance of the disposal system or are otherwise excluded by regulation.

Scenario is a subset of important FEPs that are used to identify a probable future evolution of the disposal site.

Central scenario is the scenario that the licensee can best support as to the probable future dynamic evolution of the disposal site. As a result of the site selection process for LLW disposal, the central scenario generally will not include disruptive events.

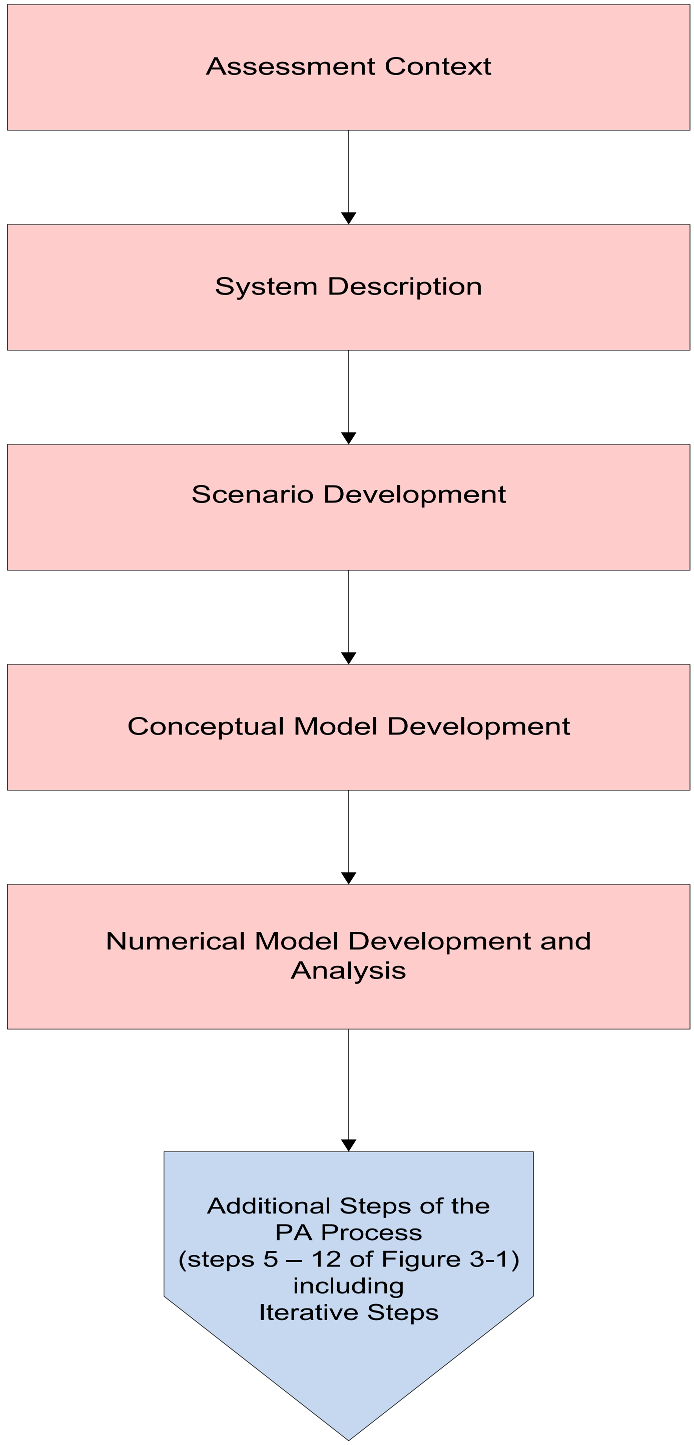

Figure 2-1 Initial Steps of the Performance Assessment Methodology

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Alternative scenario is a less likely but still plausible future evolution of the disposal site. Alternative scenarios may include disruptive events if those FEPs are relevant at a particular site.

Conceptual model is a well-defined, connected sequence of phenomena describing the behavior of the system of concern.

Alternative conceptual model is an additional and different model on how the system might work that is consistent with available supporting information. For example, a scenario may have a matrix flow conceptual model and an alternative fracture flow conceptual model; the model outputs from each may yield significantly different results.

Receptor scenario is a type of scenario that describes the FEPs associated with people becoming exposed to radiation.

Safety function is defined qualitatively as a function through which a component of the disposal system contributes to safety and achieves its safety objective throughout the analyses timeframe.

Model abstraction is the process of abstracting a conceptual model representing a dynamic site in the physical world into a *mathematical model* governed by equations that is implemented within a numerical model.

Model simplification is the process of simplifying a complex numerical model into a reduced numerical model while still maintaining the validity of the simulation results.

Code is a set of software commands used to solve mathematical equations representing phenomena of the conceptual model.

2.1.2 Level of Effort

LLW commonly contains radionuclides that are both short- and long-lived. From a specific activity standpoint, the short-lived isotopes comprise the dominant fraction of the total activity. However, when a licensee demonstrates compliance with the 10 CFR 61.41(a) performance objective, usually the radiological risk is dominated by the long-lived isotopes that remain in the inventory after the short-lived activity has decayed. LLW may contain large quantities of depleted uranium (DU) or other long-lived waste. LLW may not decrease in *risk* after a few hundred years, although it will decrease in *hazard*. LLW that contains large quantities of DU may pose a long-term risk to the public due to the in-growth of progeny.

A licensee should use a level of effort for technical analyses commensurate with the risk to the public from disposal of the waste. Specifically, the level of effort (i.e., the level of detail, comprehensiveness, completeness, and degree of iteration), is commensurate to the longevity, concentrations of radionuclides, and quantity of the waste. For example, the level of effort for the development of the technical analyses for the disposal of LLW will generally be less than that for the disposal of HLW or spent nuclear fuel. Complex modeling is generally not performed for disposal sites that contain only short-lived radionuclides and have low projected overall risk.

As an example, the completeness and level of detail of a FEPs analysis associated with disposal of LLW containing predominately short-lived radionuclides will be considerably less than a proposed LLW disposal site that will contain a large quantity of DU. Historically, as documented in earlier LLW disposals, features and processes not taken into account during the design and planning phase of a LLW disposal site can significantly reduce the isolation of the waste in question. Inadequate conceptual models and the absence of alternative conceptual models have created situations in the past in which the containment of the waste was compromised and remediation and closure of the disposal facility was necessary (NRC, 2007b). The NRC staff recommends FEPs analysis and scenario and conceptual model development for disposal sites dominated by short-lived radionuclides; however, the identification and categorization of FEPs completed by a licensee for the disposal of short-lived waste is expected to require less effort since the time period of the analysis is shorter. For longer analyses, there will be greater uncertainty. Considerably more FEPs may need to be identified, screened, and integrated into one or more conceptual models. Section 2.5 discusses the importance of identifying FEPs relevant to the waste characteristics and disposal site, as well as methods to improve the completeness of FEPs lists and scenarios.

2.2 General Review Considerations

2.2.1 Data Adequacy

It is important for a licensee to develop and use adequate data. The data should be appropriately representative and complete, of adequate quality, and unbiased. The objective of the data adequacy review is twofold. First, the reviewer should determine whether sufficient data have been provided by a licensee to support the performance assessment models. Second, the reviewer should determine whether those data have been used appropriately.

It is generally beneficial to have more data rather than less; however, some amount of incompleteness in the data may be overcome by appropriately accounting for parameter uncertainty, as described in Section 2.2.2.1.2. The types of data to be considered by licensees may include, but are not limited to site-specific data (e.g., laboratory measurements and field-scale measurements or experiments), data from analogous sites, data from generic sources, output from detailed process-level models, and expert judgment. More objective sources of data are preferred over more subjective sources of data. A licensee should review published literature even if they have made site-specific measurements. Review of published literature may help the licensee identify measurement errors or determine if the data is not representative. Expert judgment should be used by licensees as a last resort, assigned appropriate uncertainty, and completed with a formal expert elicitation process when the data are important to the performance assessment (NRC, 1996). Because performance assessments are completed with an iterative process, early data for scoping calculations may be from more subjective sources (e.g., informal expert judgment). If a licensee or regulator determines during independent analysis that certain data are risks significant; the data should be developed by more objective sources, when possible.

Because performance assessment models can simulate processes and events over a wide range of temporal and spatial scales, licensees should ensure that the data are representative of the temporal and spatial scales evaluated in the model. *Upscaling* of data may be necessary to achieve representativeness. Upscaling is the modification of data for use at a different scale, most commonly to take data from fine-scale observations for use at a much coarser scale. If a licensee uses upscaling to modify data for use at different scales, they should ensure that the key features or structure of the data important to the performance assessment are preserved. For example, precipitation may occur as short duration storm events (minutes to hours), whereas the timeframe for a performance assessment is thousands of years. If a performance impact, such as erosion of a soil cover, is a non-linear function of runoff that itself is a function of precipitation intensity and duration, upscaling of the temporal precipitation data in order to develop the performance assessment calculations may result in the loss of important detail. Licensees should use caution when estimating whether measurements are outliers, particularly when the number of measurements is sparse. Licensees should not use subjective assessments of potential outliers.

2.2.2 Uncertainty

Sources of uncertainty inherent to waste disposal in the near surface include, but are not limited to, incomplete knowledge of the natural system, its evolution, and interactions. Regulators expect that uncertainties that cannot be shown by a licensee to have a minimal effect on safety are avoided or reduced as far as possible (e.g., by means of site selection, site characterization, disposal design, and, if necessary, research). To some extent, uncertainties in the assessment results can be counterbalanced by using multiple lines of evidence, or model support. Licensees should characterize, eliminate (with justification), or bound uncertainties in their technical analyses, as well as document the impact of the uncertainties on performance.

The uncertainties in performance assessment have been classified as *scenario uncertainty*, model uncertainty (which spans conceptual model uncertainty and mathematical model uncertainty), and parameter uncertainty (i.e., uncertainty in values used in the numerical model) (NRC, 1990a). Scenario uncertainty, defined as the consideration of uncertainty in the future evolution of the site, may result in several different conceptual models for the system, distinguished by the effects of phenomena on the system. Model uncertainty may be present in each of the different submodels that comprise the overall system model. Licensees can evaluate these inherent uncertainties using *uncertainty analysis*, which is a way of formally assessing, reducing or managing, and documenting the inherent uncertainty of a system (Finkel, 1990). For example, an uncertainty analysis could provide information about where a licensee should focus model support activities, which in turn could reduce uncertainty. Parameter uncertainty is uncertainty in the parameters used in the technical analyses.

2.2.2.1 *General Structure of Uncertainty*

Some radioactive waste will present a radiological risk to humans and the environment for a long time. To help assess this risk, licensees should use predictive models that can describe the future behavior or performance of disposal systems. Building a *computational model* that combines and represents all important FEPs at an appropriate level of detail is a complex process. Uncertainties are greater for long-lived waste (lasting thousands of years or longer) than they are for short-lived wastes (lasting tens or hundreds of years). Uncertainties must be handled by licensees within the performance assessment process. Scenario development is a commonly used technique to account for uncertainties about the future.

Figure 2-2 shows a general structure of uncertainty analysis that involves separate treatments of scenario uncertainty (future uncertainty), model uncertainty, and parameter uncertainty (NRC, 1993a). Within each scenario of the future, it is possible to postulate alternative conceptual models of the behavior of the disposal system, each of which leads to a particular mathematical model to describe that behavior. For each conceptual model, it is possible to postulate alternative sets of input parameter values. In the context of performance assessment for LLW disposal, the primary purpose of an uncertainty analysis is to support a decision about compliance of the disposal system with the regulatory requirements.

2.2.2.1.1 Scenario Uncertainty

Uncertainty about the future of the site is the result of inherent lack of knowledge about how the site will evolve over time. The future climatic, geologic, and population conditions that will prevail at a site are not known, but the performance assessment process requires that a licensee consider possible future conditions. Scenario uncertainties are illustrated by considering the events or processes that may significantly influence projected doses to the *receptor*. For example, climatic variation may significantly change groundwater flow pathways over time, necessitating changes to the groundwater flow model or the introduction of new parameters. If analyses cannot exclude the possibility of either scenario 1) where the groundwater flow pathways remain unchanged (no major climate variation), or 2) where the groundwater flow pathways change (climate variation), then the site has two potential routes of evolutionary development (i.e., two future scenarios that need to be analyzed in this example). The longer the *analysis timeframe*, the greater the likelihood of significant changes to the flow path and properties. Scenario uncertainty is linked to, but not identical with, future parameter uncertainty, which is discussed in the next section.

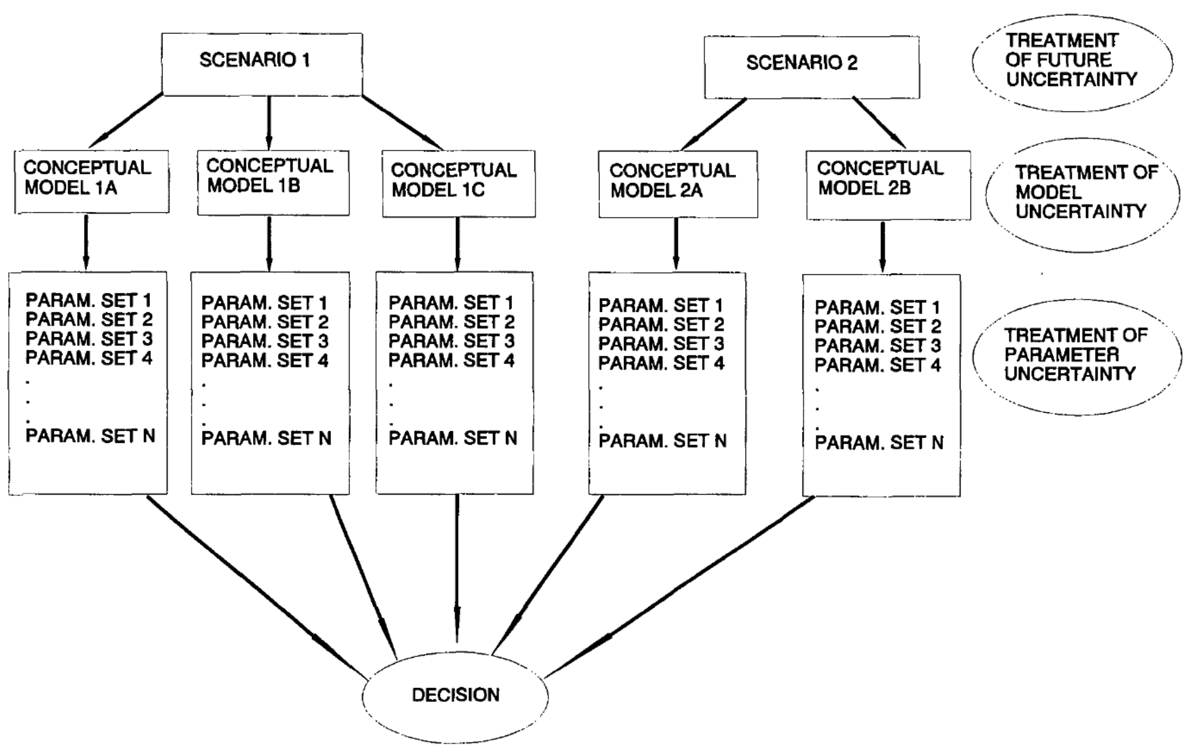


Figure 2-2 Overall Approach to Uncertainty Analysis for LLW Performance Assessment (NRC, 1993a)

2.2.2.1.2 Model Uncertainty

Model uncertainty encompasses the uncertainty in the conceptualization of the system, the uncertainty in its mathematical representation, and the uncertainty in the solution of the mathematical representation (Bonano and Cranwell, 1988). All models will encompass some simplification of reality (model abstraction) and licensees will have to make a variety of choices about the level of detail to provide.

Conceptual model uncertainty is generally the dominant type of uncertainty in a performance assessment due to limitations in the available supporting data. The conceptual model should be as complete and as appropriate to the scenario as possible. The conceptual model should be based on the information and data available and on previous experience with similar types of problems. If not all significant processes, features, or significant barriers have been considered, the conceptual model will have deficiencies and the ability of the licensee to bound or otherwise account for model uncertainty will be reduced (BIOMOVS II, 1996).

Licensees should adequately describe and document conceptual model uncertainties. The performance assessment documentation should provide the assumptions, limitations, and uncertainties of the models. Multiple representations of a model or different models may be consistent with the available data. In general, licensees should select the models that best represent available data. However, when data are sparse, multiple models may represent the available data. In this case, licensees should select the model that provides the most conservative result, or collect additional data to determine which alternative conceptual model provides the best representation. Licensees do not need to evaluate all models, but they should consider all models that are reasonably consistent with available information. Regulators should perform an independent evaluation of model uncertainty and consider whether more than one conceptual model should be evaluated, especially for complex sites.

Other types of model uncertainty include assumptions, decisions or judgments made during the development of a model, the mathematical form of the conceptual models, and the inexact implementation of mathematical models in numerical form in computer codes. Related computer model uncertainties can arise from errors in the computer code used to develop the model, input data errors, misapplication of the code (e.g., through application of the code to problems beyond the range for which the code was developed), and approximations in the solution of the mathematical model (e.g., due to inappropriate grid discretization of a domain or setting time steps that are too large).

The objective of the review of model uncertainty is for the reviewer to determine if the licensee has considered and appropriately evaluated the impact of model uncertainty. Some uncertainties are inherent in the application of predictive models to (1) long periods of time for which direct *validation* is not possible, and (2) complex systems for which measurement and characterization may be limited. These uncertainties can be evaluated in the performance assessment by (1) considering reasonable ranges in conditions and processes to test the robustness of the model, (2) by using distributions of parameters to represent the likely ranges in conditions or processes, or (3) by bounding the effects of model uncertainty by using conservative assumptions. Ideally, a licensee can minimize the impact of model uncertainty by developing as much model support as practical (see Section 2.2.3).

2.2.2.1.3 Parameter Uncertainty

Parameter uncertainty can be reducible or irreducible. Technical analyses will need to account for parameter uncertainty. Although evaluation of parameter uncertainty does not specifically address scenario uncertainty, parameter values are the building blocks of any model and therefore, spatial or temporal variations in parameter values are often needed to reflect the evolution of a site, as well as to evaluate the impact of different representations of what might happen in the future. For example, the range of flow rates through a hydrogeological unit may increase over time within one plausible scenario. In an alternative, drier scenario, the same hydrogeological unit will start out with the same flow rate, but, in contrast with the previous scenario, may decrease over time.

The objective of the review of parameter uncertainty is to determine if the assessment by the licensee includes parameter uncertainty, which techniques were used to account for parameter uncertainty, and whether those techniques adequately accounted for parameter uncertainty. Selection of conservative values is one method a licensee may use to account for parameter uncertainty. This method works well when the number of uncertain parameters is limited and conservative values can be clearly established. This method may not work well when there are many uncertain parameters, especially for complex models. This should not be interpreted by licensees or regulators to mean that conservative values should not be used for complex sites, but rather that licensees should demonstrate sufficient knowledge of their performance assessment so that conservative selections can be reliably made. Variations in the model responses, such as local minima and maxima data values, can make the determination of conservative parameter values very challenging.

Another method to incorporate parameter uncertainty is the use of some form of *probabilistic analysis*. Parameter uncertainty can be propagated through the performance assessment by distributions of variables (e.g., hydraulic conductivity, porosity, *distribution coefficient*). When using probabilistic analysis, licensees should plot measured data on figures showing the probability distributions assigned to represent the measured data in the modeling to communicate (1) the amount of data available to construct the distribution, and (2) how the selected distribution reflects the data. Licensees should preserve the correlation of data for related parameters (e.g., precipitation and irrigation rate) in probabilistic analysis, as necessary. Performance assessments that rely on a large amount of generic data (e.g., non-site-specific) will have comparatively more uncertainty, as discussed in Section 2.2.3. In a *deterministic analysis*, licensees can examine the impact of parameter uncertainty with sensitivity analyses. They can then bound impacts by the selection of conservative values. Section 2.7.4 provides a discussion of some significant challenges with this approach, as well as the metrics to use for determining compliance (i.e., the peak of the mean).

2.2.2.1.4 Uncertainty Example—Transfer Factors

One acceptable quantitative approach for modeling the transport of radionuclides through the biosphere employs steady-state transfer factors (e.g., soil to plant, water to biota) and bioaccumulation factors. The literature contains many sources for these transfer factors (Staven et al., 2003; IAEA, 1994; NRC, 1992; Wang et al., 1993; Baes et al., 1984; NRC, 2007c; NRC, 2003a). Regulatory Guide 1.109, Revision 1, "Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I," issued October 1977, provides conservative values for a variety of these factors (NRC, 1977). If available, licensees should use site-specific parameter values or ranges of values, and should document their usage. Site-specific parameter values are values measured at the site under consideration; true site-specific values are relatively rare. If site-specific transfer factors are not available, a licensee should document how their site conditions are comparable to the conditions under which the transfer factors that were used were collected. Licensees can infer transfer factors for a specific site from compilations in the literature; however, inferred values carry high uncertainty, which can be difficult to properly account for in a deterministic assessment.

Transfer factors can have very large variances and be non-uniformly distributed. These large variances may require careful treatment in the intruder assessment or performance assessment. If a transfer factor has few observations and the actual observations span many orders of magnitude, the appropriate statistic of the inferred distribution to use in the technical analysis may be difficult to determine. This is because the observations represent both inter-site and intra-site variability. The technical analysis should not benefit from inter-site variability. Use of the geometric mean, for example, may result in a high likelihood that data that are not representative of the specific site have been "credited" in the analysis. Even if intra-site values are used to extend the "conservative" end of the distribution (e.g., high values of transfer coefficients), the overall effect may not be conservative because overly broad uncertainty ranges can lead to risk dilution (Section 2.7.4). If no observations at a site are available and correlations between the specific site conditions and the conditions for which the observations were made are not available, then licensees should use conservative statistics for transfer factors in deterministic analyses. In probabilistic analyses, licensees can use the full non-truncated distribution (assuming the results are still physically reasonable), and use uncertainty analyses to determine if the uncertainty in the transfer factors is important. If the uncertainty is important, then licensees must provide a technical basis to explain why the distribution that contains inter-site variability used for the technical analysis is protective of public health and safety, or the licensee may elect to collect additional site characterization data to better define the range and variability.

2.2.3 Model Support

Model support is one of the most essential technical elements of a licensee's analyses to demonstrate compliance with the Subpart C performance objectives. Performance assessments and site stability assessments are projections many years into the future, and therefore, cannot be validated in the traditional sense. Intruder assessments are based on plausible but hypothetical scenarios. However, support for the calculations is essential for effective decisionmaking. Model support can help reduce uncertainty and provide a mechanism to determine when sufficient iteration in the development process has been performed. Regulatory perspectives on model validation for HLW disposal are provided in NUREG-1636 (NRC, 1999a). Many of the concepts found in NUREG-1636 are generic and are applicable to LLW disposal as well.

Model support can be divided into verification-type activities (i.e., determining that the equations were solved correctly) and validation-type activities (i.e., determining that the correct equations were solved). Methods for *verification* of computational models are reasonably well-established.

The objective of the review of model support is to determine if the technical analyses have adequate support to justify the estimated system performance. In addition to reviewing a licensee's QA procedures for computational modeling, the reviewer may perform independent analyses. Independent analyses may be performed with the licensee's models, with independent models, or with simplified calculations. The objectives of independent analyses are to test, confirm, or refute the licensee's assumptions and analyses.

Because the primary output of a performance assessment is dose to the public and those doses are in most cases not expected to occur until the distant future, the performance assessment cannot be supported by comparing the modeled dose to observed doses. However, a performance assessment typically includes many submodels that estimate the impact of processes such as infiltration, leaching of radionuclides from waste, and transport through groundwater. Licensees can and should support the output from those submodels using indirect methods if the output from the submodels is not observable in the real world. Model support that involves multiple sources and types of information is generally more robust. Types of model support may include laboratory or field tests, comparison to analogous systems, natural analogs, independent process modeling, formal independent peer review, and comparison to *monitoring* data.

Upon development, and through early iterations, the performance assessment model (or submodels) is likely to go through a formal or informal calibration process. Calibration is a comparison of calculated outputs (e.g., intermediate outputs such as hydraulic head in an aquifer) with measured or observed data resulting in changes to the numerical calculation to better represent the observed data. While calibration is important, it does not necessarily result in confidence in prediction. Confidence in prediction is derived through comparison of the model with independent data not used in the original development or calibration of the model. Absolute proof cannot be achieved in performance assessment modeling; however, adequate confidence in the model and modeling results is essential.

The quantity and quality of model support should be commensurate with the significance of the system/subsystem to achieving protection. For example, if the capabilities needed for an engineered barrier are consistent with past experience in similar conditions, and the barriers have similar design and quality assurance (QA), then the model support could be considerably less than for a barrier with projected capabilities that significantly exceed experience with similar barriers. When considering prior experience, licensees should ensure that the environmental conditions for the relevant degradation mechanisms are reasonably similar since many degradation mechanisms can be very sensitive to the environmental exposure conditions.

Performance assessment modeling may include the projection of performance of engineered barriers, such as engineered covers or intruder barriers, for long periods of time. Licensees should consider natural analogs for barriers desired to have very long-term capabilities (e.g., thousands of years). The greatest uncertainties in predicting future performance stem from extrapolating the results of short-term tests and observations to long-term performance. Standard approaches to development of natural analogs frequently assume implicitly that the initial conditions persist; however, the actual application of a barrier could more appropriately be viewed as an evolving component of a larger dynamic system (Waugh and Richardson, 1997). For some types of barriers, natural analogs might provide information about the possible long-term changes and can be thought of as a long-term, uncontrolled experiment.

Licensees should consider the capability of a barrier when developing model support based on analogs. For example, because of their longevity, Native American earthen mounds may provide a reasonable analog for the erosional stability of an engineered cap, but may not be a reasonable analog for other capabilities (e.g., the hydraulic performance of a cap) (Shetrone, 2004). When evaluating analogs, it is important to note that the structures that have persisted are most likely the durable structures. That is why licensees should consider analogs that have persisted, as well as those that may have experienced damage or failure. An additional complicating factor is that the initial conditions and past exposure environment for the analogs are not known and may only be estimated. However, developing an understanding of analogs increases the likelihood that a barrier may be implemented with sustainable long-term capabilities. Natural analogs are only one element of the technical basis for the capabilities of engineered barriers. Analog information should not be envisioned as providing absolute proof of future barrier performance; rather, it provides confidence that the barrier is likely to perform as intended. Analogs can be also applied to other aspects of the performance assessment models (e.g., radionuclide transport, geochemistry).

2.2.3.1 *Peer Review, Expert Judgment, and Expert Elicitation*

Different types of assessments are used in the development, review, and approval of LLW technical analyses. Scientists and engineers routinely use professional judgment in solving problems. NUREG-1563, “Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program,” issued November 1996, defines “peer review,” “expert judgment,” and “expert elicitation” as applied to HLW disposal (NRC, 1996). The NRC staff believes that those definitions and descriptions also can be applied to LLW disposal. The purpose of this section is to provide a concise summary of information pertaining to the use of experts and to remind licensees of existing sources of guidance. Methods of reviewing or supplying information to technical analyses may have different degrees of formality and independence. Information from experts is necessary when other means of obtaining requisite data or information are not practical. The types of information that experts can supply include data (e.g., hydraulic conductivity of basalt), as well as input analogous to model support (e.g., independent peer review of a hydrogeology model).

Peer review is distinguished from expert judgment in that peer review seeks judgments from experts regarding the soundness and quality of an existing or proposed scientific stance or solution to a problem. Expert judgment is information provided by experts that gives rise to or contributes to the generation of a scientific stance or solution to a given problem. Expert elicitation is a formal, highly structured, and well-documented process whereby expert judgments are obtained (NRC, 1996). The regulatory review of LLW technical analyses is essentially an independent peer review.

For all types of information obtained from experts, licensees should describe and fully document the information developed as well as the process used to obtain the information. Full documentation entails a description in sufficient detail to allow independent interpretation and understanding of the information without recourse to the author. Licensees should establish and describe the independence of the experts and their qualifications.

If a licensee uses peer review as a form of model support, the experts should have independence from the activity for their input to be of value. Otherwise, the input is essentially an extension of the original analysis. The licensee should document how the experts were selected and their qualifications. Licensees should describe the information that the experts reviewed and document when the experts’ review and input was received. In other words, scope and schedule are important in establishing the thoroughness of the review. The experts' reviews should have sufficient detail for independent evaluation by the regulator. Independent peer review is more subjective than some other forms of model support (e.g., field experiments) but may be necessary to support the technical analyses for LLW disposal.

Expert elicitation and expert judgment are means to supply information such as uncertain values or uncertainty distributions when data are unavailable or inadequate and cannot be obtained with direct methods such as experiments. Expert elicitation and judgment characterize the state of knowledge about an uncertain FEP. Expert elicitation and judgment should not be used instead of "hard" data, but rather in conjunction with those data. NUREG-1563 provides general guidelines on those circumstances that may warrant the use of a formal process for obtaining judgments of experts, as well as acceptable procedures for conducting expert elicitation (NRC, 1996).

2.2.3.2 *Model Support Example –Engineered Cover Performance*

The NRC staff is providing the following example to illustrate a reasonable effort to develop model support for the long-term performance of an engineered system. The DOE, Office of Legacy Management, Environmental Sciences Laboratory, developed a multi-faceted strategy combining monitoring, modeling, and natural analog studies to provide support for the estimated long-term performance of engineered covers (Waugh, 2004; Waugh 2006). The strategy utilized various independent sources of information to develop an understanding of the performance of engineered covers. Laboratory experiments (e.g., the hydraulic conductivity of clay), field measurements (e.g., the moisture content of the cover materials and tailings), in-situ field tests (e.g., lysimeter studies), natural analogs, and traditional monitoring data (e.g., radon fluxes, groundwater concentrations of radionuclides) provided information to compare to estimates of cover performance. There is uncertainty in any type of observational data. However, utilization of multiple sources of confirmatory information allows for the development of a more complete understanding of the uncertainties, and therefore, a lessened chance of false positive or false negative confirmation of system performance.

As part of the model support strategy, DOE obtained field measurements using lysimeters to test the performance of cover designs under the Alternative Cover Assessment Project (ACAP) (Albright et al., 2004). DOE performed comprehensive lysimeter tests of prototype covers at landfill sites across the country in climates ranging from arid to humid and from hot to cold. Some of the cover sites were at locations of full-scale covers operated by DOE. DOE monitored both conventional, low-permeability and alternative evapotranspiration cover designs in side-by-side comparisons. The ACAP prototype tests were conducted using 10- by 20-meter drainage lysimeters instrumented for direct measurement of runoff, soil water storage, lateral drainage, and percolation flux for a full-depth cover profile. DOE used the lysimeter monitoring data to develop insights into cover performance.

Because some processes that may influence the performance of engineered covers are difficult to address with short-term field tests or existing numerical models, DOE also used natural analogs to help identify and evaluate likely changes in environmental processes that may influence the performance of engineered covers (Waugh, 2006). DOE used the natural analog information to (1) engineer cover systems that mimic favorable natural systems, (2) bound possible future conditions for input to predictive models and field tests, and (3) provide insights about the possible evolution of engineered covers as a basis for monitoring leading indicators of change. DOE considered a variety of natural analogs, including analogs of future climate states at the Monticello, Utah site that were developed using paleoclimate data. A preliminary analysis of paleoclimate data for Monticello yielded average annual temperature and precipitation ranges of 2 to 10 degrees C and 80 to 60 centimeters, respectively, corresponding to late glacial and mid-Holocene periods. Additional natural analogs were developed for future soil development and ecological change.

2.2.4 Dose Assessment

2.2.4.1 *Human Activity - Scenarios*

Stylized scenarios are commonly defined to represent the human component of the analyses. Little scientific basis exists for predicting the nature or probability of future human actions over long timeframes. The use of stylized scenarios is commonly advocated by regulators in order to avoid excessive speculation. A special category of FEPs are those related to future human activities that may disrupt the disposal system. Section 4.0 provides guidance on developing scenarios for the inadvertent intruder assessment. 10 CFR Part 61 requires the consideration of inadvertent intrusion, and also, to some extent, constrains the types of receptor scenarios that need to be considered.

Licensees should integrate receptor scenarios with the scenarios describing the future evolution of the disposal site. For example, the landscape and hydrological regime at and around a hypothetical disposal site may change in response to climate change, and with these changes, receptors and their habits may change. The central scenario for this hypothetical disposal site may include *exposure pathways* that result in multiple receptor scenarios. For example, the most plausible and/or conservative receptor scenarios for an undisturbed central scenario may be the resident farmer and suburban resident receptor scenarios. However, if a licensee is evaluating an additional alternative scenario of the future involving climate change for the same site, the most plausible receptor scenario for the alternative scenario may no longer favor residential dwellings at the site, but may be, for example, occasional recreational use of the site by one or more human receptors (Figure 2-3). On the other hand, it is possible that the receptor scenarios may remain the same (i.e., the resident farmer and suburban resident receptor scenarios would be evaluated within the undisturbed future scenario and within the alternative scenario involving climate change) but the dominant pathways of exposure may change within the same scenario (i.e., irrigation rates increase resulting in additional exposure through food). (Figure 2-4).

2.2.4.2 *Receptor Scenario Development*

After releases of radioactivity to the environment, a receptor may be exposed to contaminated water, soil, air, or other media. A receptor is a *member of the public* who may be exposed to radiation from the disposal facility. Receptors include members of the public who may be on site after the institutional control period (e.g., an inadvertent intruder), as well as offsite members of the public. Section 3.4 provides guidance with respect to receptors for the performance assessment. Section 4.3 provides guidance with respect to receptors for the intruder assessment. Some of the approaches used in Section 4.3 can be applied in the performance assessment and used to demonstrate compliance with 10 CFR 61.41.

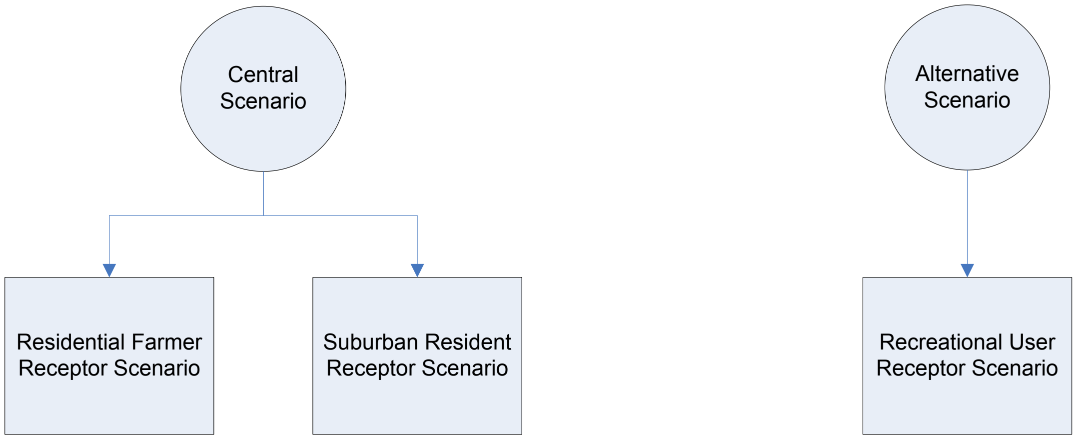


Figure 2-3 A Central Scenario with Several Plausible Receptor Scenarios, and an Alternative Scenario with a Different Plausible Receptor Scenario

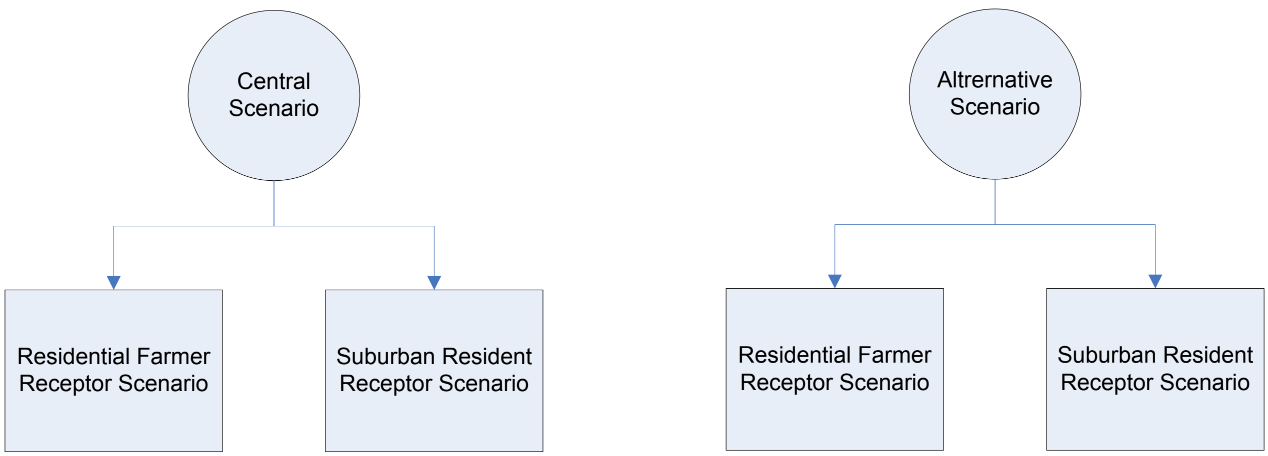


Figure 2-4 A Central Scenario with Several Plausible Receptor Scenarios, and an Alternative Scenario with the Same Plausible Receptor Scenarios

Licensees should estimate potential exposure to the average member of the *critical group*. The critical group is a group of individuals reasonably expected to receive the greatest exposure to releases over time, given the circumstances under which the analysis would be carried out. The average member of the critical group is that individual who is assumed to represent the most likely exposure situation, based on cautious but reasonable exposure assumptions and parameter values.

Scenarios of receptor exposure, also known as *exposure scenarios* or receptor scenarios, should not be confused with the general scenarios describing a future evolution of the disposal system. Receptor scenarios are a subset of the overall scenarios defined for the performance assessment (e.g., base or central scenario, disturbed or alternative performance scenarios) and intruder assessment (Figure 2-4). Receptor characteristics and receptor scenarios may vary from site to site; however, certain pathways commonly contribute to exposure to or intake of radionuclides. For example, drinking water and agricultural food production (crops, livestock) commonly contribute to radionuclide intake by many types of receptors. External exposure to contaminated soils and inhalation of resuspended contaminants are also common exposure pathways. Recreational use of surface water (e.g., fishing and swimming, which may lead to exposure to contaminated sediments) may be an exposure pathway at some sites.

The characteristics of receptor scenarios can have a large impact on the projected risks from the disposal facility. The definition of receptor scenarios can be generic or site-specific. Regardless of the specific method used to develop receptor scenarios, the licensee should provide sufficient justification for the approach used. Licensees may use generic receptor scenarios as described in NUREG-0782 (NRC, 1981a) with site-specific waste streams, or they may develop site-specific receptor scenarios to evaluate site-specific waste streams. Licensees may develop site-specific receptor scenarios by modifying the exposure pathways included in the generic receptor scenarios or build scenarios from scratch based on waste characteristics, disposal practices, site characteristics, and, when appropriate, projected land use. As the assessment time increases from the present day, the relevance of current land use to projected future land use becomes much more uncertain. For long-term assessments, dose calculations should use reasonably conservative receptor scenarios such as the generic receptor scenarios (i.e., resident-farmer or resident-gardener). The NRC staff continues to view the generic receptor scenarios as reasonably conservative to estimate potential radiological exposures to a member of the public while limiting excessive speculation about future human activities. Licensees should be cautious about adopting the generic receptor scenarios *and* exposure pathways by ensuring that the exposure pathways are appropriate for the technical analysis for their disposal site.

Licensees should provide a basis to justify receptor scenario selections. Use of conservative generic receptor scenarios would require a limited basis, whereas use of novel site-specific receptor scenarios would require more information. There may be a need to thoroughly investigate and justify the appropriateness of the selected site-specific receptor scenario(s), which may include evaluation of alternate receptor scenarios. If a licensee creates a receptor scenario based on site-specific conditions, it should provide transparent and traceable documentation of the justification for each assumption used in developing the receptor scenario (e.g., justify the inclusion (or exclusion) of a particular exposure pathway).

When assessing the dose to the receptor beyond the site boundary, licensees should consider potential receptor locations. The site boundary begins at the end of the *buffer zone*, which should extend 100 meters from the boundary of the *disposal units*. Generally, receptor locations at the site boundary would be expected to receive the greatest radiological exposures since these locations tend to minimize the opportunity for dilution that may occur at greater distances from the site. However, this may not always be the case, particularly for sites with preferential transport pathways (e.g., fracture zones) or physical constraints that might limit exposure of the receptor to the media (e.g., non-potable groundwater). Licensees should demonstrate that the selection of an offsite receptor location does not bias the outcome of the performance assessment such that radiological exposures are significantly underestimated. Receptor locations may be different for transport in various environmental media; the highest impact from an air pathway may be at a different location than the highest impact from a water pathway. However, it is not expected that the peak exposures at different receptor locations would be additive. Rather, licensees need to demonstrate that the performance objectives will be met for the location in which the receptor would be expected to receive the largest annual dose from all significant exposure pathways (e.g., peak annual all-pathway dose).

Determination of the receptor location should also consider the evolution of the site environment during the compliance period. For instance, climate change over the compliance period may alter whether the groundwater is potable or of sufficient yield and thus, potentially, the location of the offsite receptor well.

A site-specific assessment would typically consider climatic and environmental conditions. As discussed in NUREG-1573, performance assessments should consider variability in natural conditions, processes, and events (NRC, 2000a). The selection of receptor scenarios and pathways in the performance assessment and intruder assessment should consider the variability in natural conditions. For a typical commercial LLW disposal facility, where the hazard from the inventory remaining at 500-1,000 years is expected to be low and allowable limits on long-lived radionuclides can be set, licensees should avoid unnecessary speculation about major changes to future climate (such as glacier formation). This is because the human population would be dramatically affected by the natural process, and the radiological impacts would likely be secondary (in part because the inventory of long-lived waste is limited). However, licensees should consider more gradual changes in performance assessment modeling for significant quantities of long-lived radionuclides, especially for performance period analyses (Section 7.0). For example, natural cycling of climates may induce variation in the nature, timing, and magnitude of meteorological processes and events. For long-lived waste streams, licensees should consider these gradual changes when evaluating impacts to members of the public. If a licensee uses current site conditions to eliminate what would otherwise be considered credible land use (receptor) scenarios and the waste is long-lived, the performance assessment and intruder dose assessment should consider expected changes to climate and environmental conditions as a result of natural cycling of the climate. Changes to the climate may make the eliminated land use (receptor) scenarios more or less likely to occur in the future.

A licensee's assumptions about land use should focus on current practice in the region of concern, which can be as large as an 80-kilometer (50-mile) radius. To narrow the focus of current land practices, the licensee can use information on how land use has been changing in the region and should give more weight to land use practices either close to the site or in similar physical settings. Licensees should also evaluate land uses that occur in locations outside the region of concern that share characteristics (temperature, precipitation, topography) expected for the region of concern over the duration evaluated in a site-specific receptor scenario. Consideration of environmental-analog regions may help identify whether present-day land uses have been driven by past socio-economic development. Land uses primarily resulting from socio-economic development are generally more uncertain over longer time periods than land uses primarily resulting from physical conditions (e.g., climate).

2.2.4.3 *Dosimetry*

As described in 10 CFR 61.7(c)(5), the dose methodology used to demonstrate compliance with the performance objectives of 10 CFR Part 61 shall be consistent with the dose methodology specified in the standards for radiation protection set forth in 10 CFR Part 20, "Standards for Protection against Radiation." The dose methodology is how individual dose factors (for example: external, ingestion, or inhalation) are calculated for each radionuclide. Licensees may use updated dose factors, which have been issued by consensus scientific organizations and incorporated by the U.S. Environmental Protection Agency (EPA) into Federal radiation guidance. Additionally, licensees may use the most current scientific models and methodologies (e.g., those accepted by the International Commission on Radiological Protection [ICRP]) appropriate for site-specific circumstances to calculate the dose.

In the performance assessment and intruder assessment, licensees may use the dose conversion factors for inhalation and ingestion developed by the EPA as published in EPA-520/1-88-020, Federal Guidance Report (FGR) No. 11, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," issued September 1988 (EPA, 1988). Similarly, it is appropriate for a licensee to use EPA's external dose factors as published in EPA-402-R-93-081, Federal Guidance Report No. 12, "External Exposure to Radionuclides in Air, Water, and Soil," issued September 1993 (EPA, 1993). These dose factors are selected to ensure consistency of the *dosimetry* models used in deriving these factors with 10 CFR Part 20, "Standards for Protection against Radiation."

Dose conversion factors are further defined by the chemical form of each element, by either its gastrointestinal tract uptake fraction (known as the f_1 factor for ingestion dose factors), or its solubility class (solubility in lung fluid for inhalation dose factors). Licensees should provide justification in the performance assessment and intruder assessment for the chemical forms assumed, particularly if a radionuclide has more than one value (e.g., strontium or uranium). Licensees should use reasonably conservative solubility classes for modeling radionuclides in a performance assessment, considering that the element may change in chemical form as it moves through the environment before reaching receptors. For acute *intruder scenarios*, different sets of chemical forms may be expected as the chemical forms of radionuclides in the disposal unit environment may differ from those in the external natural environment.

An example of a conservative approach to selecting dose factors is used in NUREG/CR-5512, "Residual Radioactive Contamination from Decommissioning, Technical Basis for Translating Contamination Levels for Annual *Total Effective Dose Equivalent*," issued October 1992 (NRC, 1992). Appendix E, Section E.1, of Volume 1 of this NUREG describes the values recommended for use in the screening models developed for application to decommissioning. Specifically, Table E.6 gives inhalation (i.e., solubility) class and the f_1 factor for each radionuclide. Because the values are recommended for screening analyses, in most cases, the solubility class selection will maximize the potential inhalation dose. For plutonium, the solubility class represents the most common chemical form that will likely be encountered in environmental situations. For the other radionuclides, the solubility classes and gastrointestinal uptake fractions are defined for the combination resulting in the highest dose.

The licensee should use a consistent dose methodology for all the applicable performance objectives (i.e., for the performance assessment (10 CFR 61.41), intruder assessment (10 CFR 61.42), and assessing doses during operations (10 CFR 61.43)). If the licensee wishes to use a methodology not consistent with the definitions in 10 CFR Part 20, they may request an exemption from the definition of "weighting factor" as defined in 10 CFR 20.1003. For example, the licensee could request to use (1) the latest dose conversion factors (e.g., ICRP Publication 72, "Age-Dependent Doses to the Members of the Public from Intake of Radionuclides, Part 5, Compilation of Ingestion and Inhalation Coefficients," issued September 1996 (ICRP, 1996), or (2) EPA-402-R-99-001, Federal Guidance Report No. 13, "Cancer Risk Coefficients for Environmental Exposure to Radionuclides," issued

September 1999 (EPA, 1999)).[1] In SRM-SECY-01-0148, the Commission directed that the NRC staff should continue to consider and grant, as appropriate, licensee requests to use revised internal dosimetry models on a case-by-case basis (NRC, 2002a).

Licensees must select organ dose weighting factors and corresponding dose factors (i.e., extrapolation of the dose to a specific organ to the effective dose to the whole body) that were developed using the same dose methodology. For example, if a licensee uses the organ dose weighting factors specified in 10 CFR 20.1003 that were developed from the ICRP 26 dose methodology (ICRP, 1977), they should use the corresponding dose factors that are tabulated in FGR Report 11 and ICRP Report 30 (ICRP, 1979; ICRP, 1980; ICRP, 1982). If a licensee uses the organ dose weighting factors that were developed from the ICRP 60 dose methodology (ICRP, 1991), they should use the corresponding dose factors that are tabulated in FGR Report 13 and ICRP Report 72. A licensee should not select organ dose weighting factors from 10 CFR 20.1003 and dose factors from ICRP Report 72, because they were not calculated using consistent dose methodologies.

Licensees should provide justifications for age-based considerations of scenarios, *critical group* assumptions, and the chemical forms, consistent with the dose methodology system being used. Age-based considerations should evaluate the sensitivity to the total dose, rather than specific pathways.

If a licensee chooses to modify their existing performance assessment and intruder analyses based on the availability of new dosimetry information, the licensee will need to submit the updated performance assessment and intruder analysis for review and approval, similar to any other update (see Section 8.0). As stated previously, the licensee may need to request an exemption to 10 CFR Part 20 to use the latest dose conversion factors to perform dose analyses for individuals during operations to meet the 10 CFR 61.43 performance objective.

2.3 Assessment Context

2.3.1 Context of the Performance Assessment

The first step in the performance assessment process is the assessment context. In order to develop the context of a performance assessment a licensee should answer the following questions:

What is being assessed?
Why is it being assessed?
What is the scope of the assessment?

Components of an assessment context can comprise the assessment purpose, regulatory framework, assessment end points, assessment philosophy, waste characteristics, disposal system characteristics, and assessment timeframes. For LLW, the regulatory framework is

[1] The regulations at 10 CFR 20.1003 define the weighting factors, based on ICRP 26 (ICRP, 1977) that apportion the risk of stochastic effects resulting from irradiation of an organ or tissue to the total risk of stochastic effects when the whole body is uniformly irradiated. Dose methodologies that differ from ICRP 26 may deviate from those weighting factors, thus licensees must request an exemption from the definition of weighting factor in 10 CFR 20.1003 to use the alternative dose methodology.

found in 10 CFR Part 61, including the performance objectives found in Subpart C. However, the purpose of conducting a performance assessment may vary. The licensee should consider the audience for the performance assessment results. Different strategies for the performance assessment may be used (e.g., conservative vs. realistic, simple vs. complex, deterministic vs. probabilistic). A well-defined assessment context can be used to determine the level of model abstraction, as well as data and computational needs. For example, if the assessment context calls for a simple modeling approach, a relatively simple mathematical model abstracted from the conceptual model may be sufficient. In addition, the assessment context may provide a comparison point to other performance assessments. For example, if a similar site has been modeled by another organization, a comparison, and any possible discrepancies, of the model outputs will be easier to understand. For a description of an assessment context as it pertains to biosphere models for geologic disposal, the BIOMASS program, as documented in IAEA (2003), provides information and guidance.

2.3.2 Approach to Different Timeframes

This section of the guidance document describes the information that a licensee should provide and a reviewer should evaluate with respect to the timeframe for the analyses for the intruder assessment, performance assessment, and stability assessment for the compliance period, protective assurance period, and the performance period.

When completing technical analyses, the licensee should select the period of time over which the potential future behavior of the disposal system will be evaluated against the performance objectives; this period of time is termed the "*analysis timeframe*."

Licensees conduct performance assessments to understand how a waste disposal system may perform with respect to limiting releases to offsite members of the public. Performance assessments are also used by stakeholders to understand the potential impacts of uncertainties. Numerous sources of uncertainty are associated with projecting the future radiological risks from waste disposal for thousands of years, including, but not limited to, natural, engineering, and societal sources. Section 2.2.2 discusses the types of uncertainties that are commonly explicitly considered in technical analyses by licensees or reviewers.

One of the outputs of technical analyses for LLW disposal is the projected dose to a member of the public from radioactivity released to the environment. The projected doses are compared to regulatory requirements and the regulator determines whether there is an acceptable degree of confidence that the dose is consistent with the regulatory limit. In the NRC's terminology, that degree of confidence is described as "reasonable assurance." The results of a compliance analysis should not be interpreted as unequivocal proof of the expected behavior of a waste disposal facility, because of the uncertainties associated with the projected radiological risk over long time periods. Over extended periods of time, uncertainties associated with the performance of natural and engineered systems may increase, and uncertainties associated with human behavior definitively increase. In some cases, unmanageable uncertainty may be a suitable reason not to dispose of waste if the consequences have unacceptable outcomes (represented in that uncertainty). The technical analyses supply information to inform decision-makers and the public.

A three-tiered approach to the analyses timeframe is specified in 10 CFR Part 61. When implemented properly, the three-tiered approach should accomplish the main goal of licensees communicating the near- and long-term risks in an appropriate uncertainty context to regulators and other stakeholders. For discussion purposes in this guidance document, these phases are defined as follows:

Analysis timeframe — The timeframe over which a licensee should assess the projected performance of the disposal facility while factoring in the characteristics of the waste, engineered barriers, disposal site, and associated uncertainties. The analysis timeframe is divided into three phases: a compliance period, a protective assurance period, and a performance period. However, the performance period is only applicable when certain conditions are met, and therefore, it may not apply to some sites.

Compliance period — The period of time over which a licensee must demonstrate with reasonable assurance that the disposal facility will meet the performance objectives found in 10 CFR 61.41(a), 10 CFR 61.42(a), and 10 CFR 61.44. A quantitative assessment should be performed. The compliance period is defined to be 1,000 years.

Protective assurance period — The period from the end of the compliance period through 10,000 years following closure of the site. A licensee must demonstrate that releases to the environment and exposures to an inadvertent intruder have been minimized below 5 mSv (500 mrem) or to a level that is supported as reasonably achievable based on technological and economic considerations. Licensees should perform quantitative analyses for the protective assurance period (see Section 6.0).

Performance period — The period of time over which a licensee evaluates the ability of the disposal system to contain long-lived waste and demonstrates that releases are minimized to the extent reasonably achievable (discussed in Section 7.0). The performance period begins at the end of the protective assurance period and extends as long as necessary to demonstrate that the metric of the performance period can be met. Licensees should perform a quantitative assessment, though uncertainties may be large, which may decrease the confidence that a licensee should place in the results of the analyses. A qualitative interpretation of the quantitative results by the licensee is appropriate in most cases.

2.3.2.1 *Compliance Period*

10 CFR 61.2 specifies a period of 1,000 years as the timeframe over which a licensee must demonstrate compliance with the quantitative limits and stability requirements of Subpart C (10 CFR 61.41(a), 10 CFR 61.42(b), and 10 CFR 61.44). Licensees should conduct a performance assessment, intruder assessment, and site stability evaluation for the compliance period. A quantitative assessment of disposal facility performance should be developed covering the timeframe of the first 1,000 years following closure of the disposal facility. The quantitative assessment may also be risk-informed. The waste characteristics (e.g., the amount of short- and long-lived wastes), complexity of the disposal facility design, and complexity of the disposal site and surrounding environment will influence the level of detail that should be provided to support the technical analyses (see Example 2.1).

> **Example 2.1:** A facility is expected to receive typical LLW generated by commercial entities (e.g., limited concentrations of long-lived waste). The waste has average concentrations of long-lived radionuclides at or below one-tenth of the values listed in Table 1 of 10 CFR 61.55. Additionally, the facility is expected to receive waste with long-lived radionuclides that are not found in Table 1 of 10 CFR 61.55 and are at concentrations less than the natural soils surrounding the facility.
>
> **Conclusion:** A performance assessment, intruder assessment, and stability assessment should be completed to demonstrate compliance with 10 CFR 61.41(a), 10 CFR 61.42(a), and 10 CFR 61.44. Because the waste is dominated by short-lived activity and long-lived concentrations are limited, specialized models and associated model support for long-term processes (e.g., cycling of climate) are not necessary.

2.3.2.2 *Protective Assurance Period*

The protective assurance period is the period from the end of the compliance period through 10,000 years following closure of the site. The analysis for the protective assurance period is similar to the compliance period – a licensee will complete a performance assessment, intruder assessment, and site stability analyses. The primary difference between the compliance period and protective assurance period is that the objective of the protective assurance period is to minimize impacts to members of the public and the environment from the longer term releases from the LLW disposal facility. Sections 10 CFR 61.41(b) and 10 CFR 61.42(b) provide dose goals, rather than dose limits, for the protective assurance period, primarily because the process licensees may use to minimize impacts based on what is technologically and economically practical may be different for different types of wastes. A licensee must demonstrate that releases to the environment and exposures to an inadvertent intruder have been minimized below 5 mSv (500 mrem) or to a level that is supported as reasonably achievable based on technological and economic considerations. Section 6.0 of this document provides detailed guidance on analyses for the protective assurance period.

The performance assessment for the 10,000 year protective assurance period is intended to be implemented in a risk-informed, performance-based manner. The type of waste proposed for disposal by a licensee will affect the complexity and scope of the analysis. A disposal facility may contain limited quantities or low concentrations of long-lived waste. The mere presence of long-lived waste should not be interpreted as imposing a burden of quantitative technical analyses of FEPs extending to 10,000 years. It may be acceptable for a licensee to demonstrate by use of conservative exposure scenarios that concentrations and quantities of long-lived waste are sufficiently limited such that longer-term processes are unlikely to result in unacceptable doses.

A licensee could demonstrate that a facility accepting only short-lived waste could meet the regulatory requirements without a quantitative assessment of the impacts extending many thousands of years into the future. The performance assessment for a facility that accepts large quantities of long-lived waste would need to consider FEPs that could significantly affect whether the facility could meet the performance objectives for the protective assurance period, and this set of FEPs may be more extensive than that associated with the disposal of short-lived waste. Disposal of large quantities of long-lived waste will likely require a performance demonstration by a licensee that is much more complex than the evaluation of the disposal of short-lived waste. The demonstration of performance for the disposal of long-lived waste will likely require significantly more resources to complete.

Licensees and regulators should consider if radiological risk from long-lived waste is being limited by the waste characteristics or by the facility design and site characteristics. If the risk is limited by the waste characteristics (e.g., limited inventory) a long-term quantitative analysis may not be necessary. If the risk from long-lived waste is limited by the facility design and site characteristics, then a long-term quantitative assessment should be developed. It is appropriate for a licensee to use simplified calculations to determine the detail needed for the longer term assessment, as long as the simplified calculations are based on reasonably conservative scenarios and models (see Example 2.2). In other words, the NRC staff expects the process of determining the level of detail that may be needed for a longer term assessment to be iterative. In addition, a licensee should consider waste characteristics for the full protective assurance period to account for the potential ingrowth of long-lived progeny when estimating the concentrations of long-lived radionuclides in the disposed waste.

Example 2.2: A proposed facility plans to receive long-lived waste, but the licensee or applicant is unsure how much detail should be provided in the protective assurance analyses. The analyses for the protective assurance period reflect longer-term processes (those that occur after a thousand years). The licensee completes an assessment of the potential long-term risk by evaluating a resident-intruder (with conservative biosphere parameters), takes no credit for wasteforms or engineered barriers, and completes a groundwater assessment using conservative flow rates and distribution coefficients. The licensee finds that the potential doses have been minimized consistent with 10 CFR 61.41(b) and 10 CFR 61.42(b).

Conclusion: A complex evaluation of long-term processes such as landform evolution and climate change is not necessary to demonstrate compliance with 10 CFR 61.41(b) and 10 CFR 61.42(b). Disruptive processes would be expected to increase dispersion of the waste in the environment. Because the licensee evaluated the waste in an undispersed state using conservative scenarios, the licensee has demonstrated that the characteristics of the waste will ensure that long-term doses are minimized. The licensee is still required to consider the impact of disruptive processes on the demonstration of compliance with 10 CFR 61.44.

2.3.2.3 *Performance Period*

The performance period is the time after the protective assurance period when longer-term doses could result from the disposal of certain types of long-lived waste. The objective of analyses provided for the performance period is for a licensee to demonstrate that releases from long-lived waste disposed of in the facility have been minimized to the extent reasonably achievable and that the facility has been designed with consideration of the potential long-term radiological impacts, consistent with available data and current scientific understanding. The analyses should identify the features of the design and site characteristics that will reduce long-term impacts and describe the capabilities of these features. Analyses for long-lived waste should provide the range of peak annual doses that are projected to occur after 10,000 years following site closure, or other metrics such as concentrations of radioactivity in the environment and flux rates to the environment. The long-term performance period analyses are designed to complement the technical analyses performed for the compliance demonstration and protective assurance analyses (10 CFR 61.13(a), (b), (d), and (f)).

As described below, and in more detail in Section 7.0, a number of approaches are acceptable for providing the necessary information for performance period analyses. A licensee should provide sufficient information and analyses for the long-term performance period that demonstrate that the 10 CFR 61.41(c) and 10 CFR 61.42(c) performance objectives will be met. The licensee should use available data and current scientific understanding to assess the long-term performance of the waste disposal facility, including uncertainties.

The NRC staff recommends the performance period analyses should cover the period of geologic stability at the disposal site, limited to a maximum of one million years or the peak dose[2] considering uncertainty, whichever comes first. It would not be appropriate to constrain the analyses to the period of near-surface geologic stability, as one of the reasons for undertaking the performance period analyses is for a licensee to communicate to decision-makers the potential range of consequences from the disposal action. Near-surface geologic instability may result from a process such as fluvial erosion (e.g. driven by lake formation), which could have severe impacts at an unstable site. Near-surface geologic instability may indicate that the site is unsuitable for disposing of significant quantities of long-lived radioactive waste. A licensee should not use near-surface geologic instability as a basis for limiting the analysis. If the analysis for LLW disposal was limited to the period of near-surface geologic stability, the analysis could be truncated prematurely and the long-term risks and uncertainties may not be understood. In addition, instability could be used as a basis to select a site, which is not acceptable. Section 7.0 provides more detail on specific technical issues that may be relevant to technical analyses for the performance period.

2.3.2.4 *Site Characteristics*

Site characteristics are identified in 10 CFR 61.50 that either must be avoided or must be present at a proposed disposal site. As described in the concepts section (10 CFR 61.7), a licensee needs to consider site characteristics in terms of the indefinite future, taking into account the radiological characteristics of the waste. They should evaluate site characteristics for at least a 500-year timeframe and understand that the interpretation of the indefinite future is different for different types of waste. Flexibility is provided to licensees to ensure that they can consider site characteristics in a risk-informed manner. The site suitability requirements are designed to be applied to ensure that the long-term performance objectives of Subpart C are met. A cornerstone of radioactive waste disposal is the stability of the disposal system. Sites for which the site characteristics requirements cannot be satisfied are unlikely to meet this primary regulatory objective.

For the disposal of any type of waste, the hydrological site characteristics identified in 10 CFR 61.50 are required[3] for the next 500 years. For example, disposal should not be

[2] As discussed in Section 7.0, the performance period analyses may include metrics other than dose (e.g., concentration, fluxes). See Section 7.0 for more detail.
[3] 10 CFR 61.50 lists the hydrological characteristics a site is required to have as well as other hydrological characteristics a site must not have.

permitted at a site where the facility is expected to be in the 100-year floodplain over the next 500 years. 10 CFR 61.50(a)(4) specifies other characteristics of the site that should not be present at any timeframe because they significantly affect the ability of the disposal site to meet the performance objectives of Subpart C (e.g., population growth, tectonic processes). Appendix B presents currently understood hazard maps related to the features and phenomena of the 10 CFR 61.50 criteria.

Whether a licensee's consideration of site characteristics needs to be extended to the end of the protective assurance period (i.e., 10,000 years) or into the performance period depends on the type of waste that will be disposed. For a disposal facility that only accepts short-lived waste and also contains minimal quantities of long-lived waste, a licensee's consideration of the site characteristics over the next 500 years would ensure that a proper site has been selected and that it would be capable of being characterized, modeled, analyzed, and monitored. A licensee is not prohibited from considering site characteristics for more than 500 years, and it may enhance the robustness of their technical evaluation. However, a consideration of site characteristics for more than 500 years for the disposal of waste with limited long-lived radioactivity would be unnecessary. To determine if the amount of waste a licensee wishes to dispose of is a minimal quantity, a licensee may simply calculate the product of the projected facility volume (or mass) and the concentrations provided in the table in 10 CFR 61.13(e), then apply the sum of the fractions rule for mixtures of radionuclides described in 10 CFR 61.55(a)(7). In this context, a minimum quantity is defined as the product of volume and concentration of waste that corresponds to a sum of fractions of one tenth.

The timeframes that reviewers should use to evaluate the site characteristics requirements are:

A) If $C < 1/10^{th}\ X \Longrightarrow$ evaluate 500 years

B) If $1/10^{th}\ X < C < X \Longrightarrow$ evaluate 10,000 years

C) If $C > X \Longrightarrow$ evaluate performance period

where C is the disposal site waste concentration sum of fractions for long-lived waste, and X is the 10 CFR 61.13(e) Table A sum of fractions. By providing a value for long-lived alpha-emitting radionuclides in Table A, most isotopes of concern (including uranium isotopes) will be considered using this approach. However, in some circumstances a disposal facility's inventory may contain other long-lived isotopes. If there are long-lived isotopes that are observed to be key contributors to projected risk that are not included in Table A (e.g. Cl-36), a licensee should evaluate the site characteristics over a timeframe as long as necessary to support the relevant performance demonstration. In most cases the licensee would have performed this iterative evaluation (from characterization to performance analyses and back to characterization) prior to submittal of the analyses to the regulator.

2.4 System Description

The second step of the performance assessment process is for the licensee to describe the LLW disposal system and the natural environment of the site. The objective of the system description review is to ensure that the information that was used to develop the performance assessment models and the information describing the overall disposal system have been adequately described. The description should be adequate to allow an independent reviewer to understand the LLW disposal system. The system description should provide, at a minimum, information describing:

- The site;
- The natural setting;
- The disposal facility;
- The interaction of the site and disposal facility;
- The waste to be disposed of including its radiological, chemical, and physical characteristics;
- Potential disruptive processes; and
- The characteristics of members of the public potentially affected by the facility.

The specific technical information that must be provided is listed in 10 CFR 61.12. The system description should provide estimates of the temporal changes to the aforementioned information, especially for disposal of long-lived waste. A practical metric to determine if the system description is adequate is if the system can be understood without seeking clarification from the document authors.

2.5 Scenario Development

The third step in the performance assessment process, scenario development, is the process of developing the scope of the analysis that will be implemented in the conceptual and numerical models. Development of a model that represents the current and future features, events, processes, and their interactions, is a complex process. Formal approaches to scenario development are usually either bottom-up or top-down. The bottom-up approach involves the identification, categorization, and systematic screening of FEPs. The top-down approach uses the *safety assessment* and safety functions to develop scenarios.

Typically a process or event acts upon a feature, and as time progresses, processes and events (both can be referred to as a *phenomena*) act to modify the system. A comprehensive set of FEPs or safety functions should capture all of the features and phenomena that are potentially relevant to the near- and long-term performance of a disposal system.

For the bottom-up approach, the FEPs analysis developed by a licensee should produce a FEPs list at a level of detail that is broad enough to produce a systematically categorized but manageable number of FEPs, yet specific enough to provide the complexity required for screening and/or modeling. From this set of potentially relevant FEPs, a licensee can define a subset of FEPs that are used to identify a probable future evolution of the disposal site (i.e., a *scenario*). The licensee can develop a connected sequence of FEPs describing the behavior of the system of concern (i.e., *conceptual model*). Remaining FEPs not incorporated into the original or central scenario may include disruptive events. Relevant FEPs not incorporated into the central scenario form the basis for alternative scenarios. Usually, the *central scenario* does not include disruptive events (e.g., earthquakes, volcanoes) while *alternative scenarios* of the same site may or may not include disruptive events, depending on the results of the scenario development.

The description of how the disposal system will function, given the FEPs comprising the scenario, is the conceptual model. A qualitative description of the conceptual model would include how the FEPs and significant barriers interact with one another and how the site functions (e.g., porous or fracture flow, precipitation, dissolution, degradation, erosion) for each scenario. Plausible *conceptual models* of a system are estimates of how the system may function. The distinction between a scenario and a conceptual model is not very sharp and can be somewhat blurred during the performance assessment process. It is important that the complete set of scenarios developed by a licensee represents the full range of possible future states of the disposal system, and that the complete set of associated conceptual models incorporate all of the retained FEPs.

Scenarios are often assembled and classified based on their likelihood of occurrence. For example, the terms “central,” “base case,” or “nominal” scenarios are often used to describe the expected future state of the system. “Altered evolution” or “alternative” scenarios are typically considered less probable but still plausible, while implausible “what if” scenarios may be used to explore the robustness of the system. “Stylized scenarios” may be used to represent future human actions. Receptor scenarios are subsets of scenarios and describe the end process by which people may become exposed to radiation. A residential farmer receptor scenario, for example, is a general description of the pathways leading to possible exposure and of the behavior and lifestyle of the hypothetical receptor. The relationship between scenarios and receptor scenarios is discussed further in Section 2.2.4.1.

A *safety function* is defined qualitatively as a function through which a component of the disposal system contributes to safety and achieves its safety objective throughout the analysis timeframe. Safety functions are used in the top-down approach to scenario development.

Often, performance assessments will exclude scenarios from the base case based on the scenario development process but will evaluate scenarios called “what if” scenarios. These “what if” scenarios include scenarios of varying likelihood – some may be plausible whereas others are extremely unlikely. Many “what if” scenarios originate from specific concerns expressed by stakeholders. They can include very conservative scenarios that would normally have been rejected in a scenario development process due to very low probability of occurring or low impact on the results. If stakeholder interest is very high, scenarios that are usually excluded during the scenario development process could still be included in the performance assessment analyses; however, these scenarios would usually be labeled as very unlikely to occur and would not be considered as a valid alternative scenario by the analysts. With “what if” scenarios, distinctions between likely and very unlikely scenarios are not made since they were constructed outside of the scenario development process. As a consequence, the interpretation of the results may be difficult since it is not clear which results are realistic and which ones are very unlikely. Commonly in these cases, all the results are discussed; however, they are not included in the decision-making process since the results are considered unrealistic (even though some of the scenarios may have been valid alternative scenarios of future conditions and events). Therefore, it is generally recommended that licensees avoid “what if” type scenarios and complete the full scenario development process. If “what-if” scenarios are used, a qualitative or quantitative likelihood of the scenario should be developed to provide context for the results.

2.5.1 Scope of Analysis

A performance assessment does not need to incorporate all FEPs for a disposal site. The performance assessment should include those FEPs that can either individually or in combination impact the disposal facility's ability to meet the performance objectives. Because the significance of FEPs to performance may be difficult to determine a priori, FEP screening a performance assessment model development are usually iterative processes.

Some events and processes may be interrelated. For example, a large rainfall event may cause erosion, as well as damage to a protective layer that then allows more erosion in the future. A process such as erosion may be driven by events of variable frequencies and duration. Strict classification of phenomena into events or processes is not as important as ensuring that licensees include the combinations of events and processes that may significantly impact the performance assessment.

Different approaches may be used to define and screen the FEPs relevant to a particular disposal facility. A licensee using internal (i.e., in-house) subject matter experts to define the scope is an example of informal definition of the scope of the assessment and is appropriate for simple sites and short-lived waste inventories. A formal process, as discussed in detail in the following sections, may use internationally defined lists of FEPs (NEA, 2002) with independent technical review, which is appropriate for complex sites and long-lived waste inventories. The purpose of defining and screening FEPs is to ensure completeness of the evaluation. Whether a formal or informal process is used to define and screen FEPs, the assessment should provide the following information:

- A clear description of the FEPs included in the assessment;
- A description of the FEPs that have been excluded from the assessment and the bases for their exclusion; and
- A description of the process for determining the significance of FEPs and a consideration of combinations of phenomena for FEPs excluded on the basis of significance.

Licensees may exclude FEPs from the assessment based on regulations or due to lack of relevance (probability) or limited impact (consequence) during the compliance, protective assurance, or performance period, taking into account the proposed inventory for the disposal site. The scope of a performance assessment model can be established through either a top-down or bottom-up approach, as discussed in Section 2.5.3. The bottom-up approach involves the development of an FEP list followed by a screening process to determine which FEPs may apply. The bottom-up approach is commonly used for complex sites. The top-down approach involves the addition of content to a performance assessment model based on the input from subject matter experts. Both approaches may be iterative.

A licensee may use an iterative process for FEP identification and selection. As the performance assessment model is developed, new information needs may be identified which will allow a licensee further refine the scope of the performance assessment. It may be possible for a licensee to demonstrate that the performance assessment is complete without a formal FEP identification analysis. This is more likely for simple sites and short-lived waste inventories. For complex sites and long-lived waste, the likelihood decreases that the performance assessment can be demonstrated to be complete without an iterative FEP identification and screening process. Example 2.3 provides some guidance on determining whether a site is simple or complex.

Lists for FEPs (FEPs lists are discussed in Section 2.5.3.1.1; a generic FEP list for LLW disposal is found in Appendix C) can be quite extensive. Some amount of aggregation may be necessary to make the screening, assessment, and implementation process manageable. On the other hand, lists that are too general will not be useful, as key FEPs may not be included at the implementation stage or may not be included with appropriate responses and functional behavior because of the coarseness of their definition. The licensee should consider whether inclusion of the FEP at the next level of detail would improve the assessment of system performance. In either case, a licensee should demonstrate that the FEPs included in the analysis are sufficiently comprehensive. Because LLW disposal has been performed at facilities throughout the world, the licensing and operational experiences of other disposal facilities can provide a good starting point for licensees at a new facility.

Example 2.3: Is my site simple or complex?

Simple sites are generally characterized by few disruptive processes, limited fast transport pathways, relatively homogeneous geology, high stability, and stable climatic conditions. Complex sites have higher uncertainty, driven by more disruptive processes (individually and with cumulative effects); complex geology including fast pathways such as fractures; decreased stability; and more highly variable climatic conditions. When there are more processes that can lead to significant releases, there will likely be greater complexity in the performance assessment of the site. The interpretation of site complexity will also be influenced by the type of waste disposed. If the inventory of waste to be disposed of is limited, relatively simple conservative analyses may be appropriate even for a complex site. Disposal of significant quantities of long-lived waste decreases the confidence that stability can be assured and increases the variability in climatic conditions that could be significant within the assessment period because of the consideration of longer timeframes. In addition, the longer timeframes mean that unlikely disruptive events will be more likely to occur within the period of assessment.

The analyses required to develop scenarios are closely linked with conceptual model development and model abstraction. FEP screening and scenario development are increasingly used as a means to build confidence in the scope of a performance assessment. The more complete the licensee’s analysis, the more likely they will be able to gain confidence from the reviewers and stakeholders. When a licensee develops scenarios, the scenarios can be used to focus stakeholder attention on the key technical issues. Scenarios provide an important area for communication among various stakeholders and an opportunity to discuss and reach a consensus on areas of specific importance. Licensees can discuss their use of scenarios and provide a rich and accessible means for public involvement.

One of the main purposes of FEP screening and scenario development for a radioactive waste disposal system is to use scientifically-informed expert judgment to guide the development of descriptions of the disposal system and its future behavior. Scenario uncertainty is handled directly by describing alternative future states of the system and by allowing for a mixture of quantitative analysis and qualitative judgments; however, it is not an attempt to predict the future. The aim is to investigate the importance of particular sources of uncertainty and provide meaningful illustrations of future conditions to assist in the decision-making process (NEA, 2001).

2.5.2 Role of Qualified Specialists

The technical basis for FEPs screening and the approach to scenario formation depends to a significant extent upon the judgment of the individuals performing the study. The completeness of a FEPs analysis can be enhanced by including a broad range of people and diverse sources of information. It is usually better to identify and categorize a range of broadly-defined FEPs to ensure comprehensiveness of the FEP process. If appropriate expertise is not available internally, a licensee may need to seek the input from experts external to their organization (i.e., professionals in the field of concern such as hydrogeologists, geomorphologists, seismologists, chemists, etc.). Licensees should obtain information from different sources, a variety of methods, and from all relevant disciplines. Licensees should document decisions based on expert judgment. The qualifications of the analysts performing the FEPs screening are also very important.

2.5.3 Approaches

There are several methods that can be used by licensees to identify FEPs, screen FEPs, and construct scenarios. A licensee should ensure that the process is systematic, comprehensive, logical, traceable, and transparent. Different approaches to scenario formation include bottom-up, top-down, and a mixture of the two.

In bottom-up scenario formation, the screened FEPs are combined to form a limited number of scenarios for consequence analysis. Sandia National Laboratory developed a structured approach to scenario selection for the NRC (NRC, 1993a). Initially, this approach was applied for disposal of HLW, but was later expanded to disposal sites for other radiological *source terms*. When using a bottom-up approach, the licensee should develop a comprehensive list of FEPs as a starting point. Development of a comprehensive list typically involves the use of generic FEPs lists and the identification of other site-specific FEPs. This is followed by a screening process to exclude certain FEPs from further consideration. The retained FEPs are combined into scenarios for evaluation. FEPs screening criteria may include prohibition by regulation, low probability, or limited consequence. The scenario in which disruptive events do not occur is usually identified as the central scenario and represents a continuation of the estimated present day undisturbed conditions. However, in some cases the central scenario could include disruptive processes if they are expected in the normal future evolution of the site. The projection of present day conditions into the future may include dynamic effects. In other words, a licensee should not interpret ‘undisturbed’ as ‘static’. For example, degradation of engineered barriers may be part of a central scenario.

In the top-down approach, licensees develop scenarios based on analyses of how the safety functions of the disposal system may be affected by possible events and processes. First, the licensee should identify the safety functions of the waste disposal system and then consider the combination of conditions that could affect one or more of the safety functions. The top-down scenario development approach used in the assessment of HLW disposal consisted of iterative steps and is described in detail in NEA (1992). While the NEA (1992) document may serve as an example of the process, a lower level of effort should be appropriate for LLW disposal.

Scenarios derived from a top-down approach typically include uncertainties potentially affecting the safety functions (e.g., barrier performance). However, in order to ensure completeness of the processes and events used to establish scenarios, a licensee may need to take advantage of systematic and comprehensive databases of the underlying FEPs. In other words, information typically used in a bottom-up approach may be useful for a licensee to consider in a top-down approach.

Regardless of the method used for developing the scenarios, phenomena and barrier components that could significantly influence the performance of the disposal system should be addressed in the assessment. Hence, a licensee should show that potentially significant transport pathways have been considered and that possible evolutions of the disposal system have been taken into account. Licensees should give specific consideration to events that could occur repetitively during the assessment timeframe (e.g., droughts, floods, and earthquakes). They should consider the performance of the disposal system under both present and future conditions.

All of the methodologies share the same basic approach, namely that a central scenario is considered a starting point. A licensee should demonstrate that relevant FEPs have been taken into account when developing alternative scenarios. Alternative scenarios are generally less likely than the central scenario. Alternative scenarios can be developed on the basis of disturbances to the normal evolution of the disposal system or to represent different amounts of degradation of the safety functions. If uncertainty is high, it may be difficult to classify different scenarios as central or alternative.

A licensee should explain and justify which scenarios are regarded as representing the expected evolution of the system, and which scenarios address FEPs having an unlikely probability of occurrence. The range of future physical environmental conditions at the site and the range of potentially exposed groups should be identified. Licensees and regulators usually assume that humans will be present and that they will make use of local resources. It is appropriate for licensees to assume that humans in the future will have similar habits to present humans, except where this is clearly inconsistent with the assumed variations in climatic conditions at a site. Section 2.2.4.2 provides additional guidance to licensees on the development of receptor scenarios.

If disruptive events are represented in a probabilistic performance assessment model, a licensee should conservatively assign the probabilities of an event occurring if the frequency of the event is not known. Formal expert elicitation may be necessary to define event frequencies. Alternatively, the licensee may represent a range of scenarios to capture the potential effects of disruptive events, without weighting the potential scenarios with probabilities. Some understanding of the likelihood and frequency of disruptive events is still likely to be necessary for decisionmakers, unless the dose projections resulting from the evaluation of disruptive events are below regulatory limits. Section 2.2.3.1 provides additional information of expert elicitation.

2.5.3.1 ***Bottom-Up Approach***

2.5.3.1.1 Identification and Categorization of FEPs

A large number of FEP lists, catalogs, and databases have been developed in different countries and encompass a range of radioactive *waste types*, disposal system designs, and geological environments. The size of these FEP lists varies, as do the content and level of detail of entries. A listing of international published FEP lists, catalogs, and databases have been compiled by NEA (2002). Licensees should perform a literature search when developing their scenario analyses because FEP lists continually change as scientific information is developed. Licensees may want to consider the generic FEP list for LLW disposal that the NRC staff developed in Appendix C of this document.

2.5.3.1.1.1 Identification and Categorization of Present FEPs

In order for a licensee to identify FEPs important to LLW disposal at their site, they should review existing FEP lists. The first step in the identification and categorization process consists of reviewing the information provided by the assessment context, as it relates to the performance assessment of the site. For example, legislation or regulatory guidance may predetermine some individual or categories of FEPs that a licensee should consider (e.g., future human activity, the biosphere system, or the future climate states). A licensee could use a previously compiled generic FEPs list as a starting point to save time and effort. They will need access to information and documents pertaining to the characterization and description of the site being considered.

The identification and categorization process may be iterative. Initially, the licensee may identify and categorize the FEPs assuming the site has static conditions. Often the central scenario can be constructed from present FEPs if the proposed disposal site is in an area of geological and geomorphological stability. Next, dynamic conditions such as natural degradation processes are assumed to affect the natural and engineered barriers. This approach is described in the following steps:

(1) Use a generic list to identify features and processes that are currently present. For this step, features or processes likely to be there in the future or that existed only in the past should be temporarily set aside until the next phase, as discussed in Section 2.5.3.1.1.2.

(2) Eliminate features and processes in Step 1 that have no potential to affect performance.

(3) Add features and processes that have occurred relatively recently (i.e. within 100 years); not events that have occurred in the long distant past (e.g., glaciers) or that may occur in the long-term future (these will be identified later as discussed in Section 2.5.3.1.1.2).

The identification step is followed by, and closely linked to, the categorization step whereby FEPs with certain similar properties are grouped together. Categorization provides a framework for organizing the scenario development process and the subsequent assessment. In addition, it provides information on interactions and interrelationships between FEPs. The primary objective is to uncover missing factors, therefore, categories that examine the system from different viewpoints should be used (NEA, 1992).

Examples of categorization include:

- Dividing FEPs related to either natural, human, or waste into separate categories;
- Providing categories according to the time scale during which different events and processes occur;
- Providing categories of FEPs related to either near-field, far-field, or biosphere;
- Categorizing FEPs according to combinations of different magnitudes of the probability and the consequence; and
- Classifying according to scientific discipline.

2.5.3.1.1.2 Identification and Categorization of Future FEPs

In the previous section, the NRC staff suggested that a licensee obtain the first FEP list by assuming the proposed disposal site is not intrinsically dynamic. However, the NRC staff recognizes that most proposed disposal areas are dynamic (e.g., shifting wind deposition and erosion). Each disposal site will be in its own state of equilibrium or disequilibrium. Most sites are chosen because the area is close to equilibrium (i.e., in an area of geological and geomorphological stability). Events that do occur may be limited in scope, and therefore, are unlikely to have a significant impact on performance of the proposed site.

For some sites, a few hundred years may be sufficient to result in significant changes to the disposal site, which would make use of a present-day FEP list incomplete. Changes can occur over different temporal and spatial scales. Some, such as the clearance of woodland and its replacement by farmland, might occur over relatively short timescales. Others, such as the closing of open water bodies by the deposition of sediments and changes to the topographical landscape, may occur over longer timescales and can be considered to be gradual processes.

The NRC staff suggests that a licensee continue the identification process after the completion of the steps listed in the previous section. Features and processes should be identified that may occur during the analysis timeframe based on documentation and studies of the past natural history of the area. Processes identified should include processes that are expected to occur over the entire time period of interest (e.g., leaching, dissolution, fracturing). The analyst or *qualified specialist* should always be aware that this step is for the purposes of identification and categorization of potential FEPs; systematic screening of FEPs occurs in the subsequent step. Some processes may have slow to moderate rates but may be episodic in nature. It would be appropriate for a licensee to consider episodic processes if the effect of the process on the disposal system could be significant.

A licensee can identify future FEPs through a qualitative exercise that should not necessarily involve original research or an effort that would take an extended time to complete; however, it will require the time of qualified specialists and may involve literature searches. Examination of past local natural history can often result in the identification of processes that may have been relevant at a site in the past and could be an indicator of potential future behavior. This past history can be used as a basis to identify and categorize a FEP for further consideration. For example, a present day desert environment may have had higher average annual precipitation rates in the past with a higher density of rivers and lakes (e.g., Lake Manly covering Death Valley in the past) and different distributions of fauna and flora. If the past environment is considered plausible in the future for the analysis timeframe considered, the associated FEPs from this past environment would be used as a basis to identify and categorize a FEP for further consideration. Some of the FEPs from the present will persist in the future, however, some processes may stop (e.g., groundwater recharge due to permafrost) and other features may appear (e.g., a forest which was previously scrubland).

As discussed for the performance period analyses in Section 7.3, more low-frequency events may be included in the FEPs list for the performance period than may be included in the FEP list for the protective assurance period (e.g., an event with a 10^{-6} per year frequency would be unlikely in a 10,000 year period but likely in a 1,000,000 year performance period). In addition, if the same set of FEPs is appropriate for both analyses, they may need to be represented differently in each analysis due to the longer timeframe and potentially altered conditions.

2.5.3.1.2 Systematic Screening of FEPs

A licensee should perform systematic screening of identified FEPs and should determine the subset of FEPs important to disposal system performance, documenting the basis for excluding or including a FEP for further consideration. A licensee should use clear and justifiable criteria. Screening approaches can vary from using some type of 'importance' ranking scale (e.g., 0 through 10), or simply an 'include' or 'exclude' system. Exhaustive analysis of importance is not necessary for FEP screening for LLW disposal. Simple calculations or bounding estimates can assist with the selection. Licensees should document the assumptions, data, or empirical information used to make these determinations. They should perform the screening process on a site-specific basis, and evaluate FEPs or FEP categories one at a time against a screening criterion. During the screening process, interactions between FEPs should be considered. If there are uncertainties as to whether a FEP can be screened, then it should be retained. The FEP can be revaluated at a later stage in the screening and evaluation process.

The following subsections discuss various aspects of screening of FEPs. The regulatory aspect is considered first since these screening criteria are legal in nature and take precedent over other screening considerations.

2.5.3.1.2.1 Regulatory

FEPs can be screened out based on inconsistency with applicable regulations. The NRC approach to analyzing timeframes is based on a compliance period of 1,000 years, a protective assurance period through 10,000 years following closure of the disposal site, and a performance period of undefined duration during which a licensee must demonstrate that effort has been made to minimize releases to the extent reasonably achievable. The performance assessment should reflect changes in FEPs of the natural environment such as climatology, geology, and geomorphology. The scope of the FEPs considered does not need to be expanded unless information is available to do so.

Section 10 CFR 61.50 is an important regulation that affects the FEPs screening process, as it provides the disposal site suitability requirements for the land disposal of LLW. The process to determine if some of these criteria will be met is complementary to the FEPs process. The criteria from 10 CFR Part 61.50 associated with the process of FEPs analysis are 10 CFR 61.50(a)(2)(i-iv), 10 CFR 61.50(a)(3) and 10 CFR 61.50(a)(4)(ii-iv).

Appendix B includes hazard maps related to the features and phenomena of these criteria. The hazard maps provide a coarse estimate of impacted areas. The hazard maps may be used to inform reviews of FEP screening associated with 10 CFR Part 61.50 requirements.

Site suitability requirements are treated differently in 10 CFR Part 61 depending on the type and timeframe. Historically, hydrological FEPs were the key drivers of poor performance of early (pre-10 CFR Part 61) LLW disposal facilities. Therefore, hydrological characteristics of the site are treated differently from other site characteristics. Regardless of the type of waste disposed, the hydrological site characteristics are either required to be present for disposal for the 500-year timeframe (e.g., the site must be generally well-drained) or should not be present for the 500-year timeframe because they will adversely affect the performance of the disposal site (e.g., waste may not be disposed of in the zone of water table fluctuation).

After the 500-year timeframe, the evaluation of hydrological site characteristics can consider the impact of the characteristics on a licensee's ability to demonstrate that the Subpart C performance objectives would be met. Disposal systems with water challenges in the present day and foreseeable future are not amenable to stability and defensible modeling and assessment. Table 2-1 provides the analyses that should be completed for the disposal site suitability requirements in 10 CFR 61.50 that are not excluded based on FEP screening.

Table 2-1 Analyses Required for Included FEPs Based on 10 CFR 61.50

Characteristic Type	Timeframe (years)	Analyses
Hydrologic	Less than 500	None – site not suitable for disposal of low-level waste
	Between 500 and up to 10,000	Stability analyses Performance assessment[1] Intruder assessment[1]
	Greater than 10,000	Performance period analyses
Non-hydrologic	Less than 10,000	Stability analyses[2] Performance assessment[1] Intruder assessment[1]
	Greater than 10,000	Performance period analyses

[1] If the stability analyses show that the site is stable with the included FEPs (e.g., design-based approach) then these FEPs would not need to be included in the performance assessment and intruder assessment.

[2] The stability analyses for included non-hydrologic FEPs may be based on demonstrating that the 10 CFR 61.41 and 10 CFR 61.42 performance objectives will be met.

Screening of FEPs Based on the Requirements in 10 CFR 61.50

> **10 CFR Part 61.50(a)(4)(ii)**: *Areas must be avoided having known natural resources which, if exploited, would result in failure to meet the performance objectives of Subpart C of this part.*

Categories of FEPs should be reviewed for known natural resources (i.e., for natural material currently considered to be a resource and whose range and scope is currently known). Calculations or estimates on the adjustment in value of a natural resource beyond a decade are not required. If review of the FEPs determines that natural resources of the type described in 10 CFR Part 61.50(a)(4) exist near a proposed disposal site and are likely to be exploited, resulting in failure to meet the performance objectives of Subpart C, then the site is not qualified for LLW disposal.

The NRC staff recommends that a future licensee survey and evaluate an area for potentially exploitable natural resources within a radius of five kilometers from the future boundary of a land disposal facility. For potential disposal sites located within valleys or in a riparian setting, a licensee should consider surveying and evaluating further than five kilometers in the upstream direction since gravitational forces on air, water, and materials may allow disruptive influences from the exploitation of natural resources to travel greater distances downstream.

> **10 CFR Part 61.50(a)(2)(i)**: *Waste disposal shall not take place in a poorly drained site or a site subject to flooding or frequent ponding, or in a 100-year flood plain, coastal high-hazard area or wetland, as defined in Executive Order 11988, "Floodplain Management Guidelines".*

A licensee must demonstrate that the disposal site is not located in a projected 100-year floodplain or a permanent or periodic wetland for a period lasting 500 years after closure. Section 2.4.1, Appendix A in NUREG-1200 provides additional guidance. For the ensuing period beginning 500 years after closure of the disposal site the licensee may, in accordance with 10 CFR 61.50(a)(3), demonstrate that the condition will not exist or that the 10 CFR 61.41 and 10 CFR 61.42 performance objectives can be met irrespective of the condition. There are two main geomorphic zones to consider: (i) coastal areas, and (ii) flood plains and wetlands.

Coastal Areas
Coastal high-hazard areas are described as having a high hazard status due to various factors including proximity to the coastline and elevation of the site. Both the present and future should be considered and estimated for this criterion. Two aspects are important for the present and the future: Vulnerability to erosion and vulnerability to flooding.

Vulnerability to Erosion: Possible FEPs that could cause detrimental erosion rates include increased rainfall and/or an increased gradient (and therefore, an increase in the erosional power of any runoff) due to changes in future climate states. As for the increased precipitation, the magnitude of the probable maximum precipitation/probable maximum flood (PMP/PMF) is not likely to change significantly in a wetter climate, based on the conservatism associated with the estimation of the PMP and the proper computation of the PMF. If the FEP, future erosion, cannot be excluded, it should be included in the analyses described in Table 2-1.

A drop in sea level could change the erosion rates of certain coastal areas due to an increase in topographic gradients. Sea level variations have been documented by various organizations and there is a general consensus that sea levels have dropped to 110 to 120 m below current sea level during the glacial periods of the current Quaternary ice age (NOAA, 2008; Gornitz, 2007; IPCC, 2001). If a proposed disposal facility is associated with a coastal area, the licensee should perform an erosion analysis assuming a sea level drop of 120 meters (m). Other drop magnitudes may be evaluated if a licensee provides adequate technical basis for the magnitude of the sea level drop. The licensee needs to analyze subsequent changes in erosional force due to sea level drop and evaluate the estimated effects on a future disposal cell.

Vulnerability to Flooding: FEPs that could cause detrimental flooding and may exist in future climates include increased high tides due to higher sea levels and potentially higher storm surges. Partial deglaciation of the Greenland ice sheet and the West Antarctic ice sheet cannot be excluded within a million year timeframe and would contribute a 4 to 6 m or more sea level rise during the performance period. For performance period analyses on the order of 10^6 years, high-tide levels near a proposed disposal site could be estimated assuming a sea level increase of 5 m. A licensee may provide a technical basis for the variation in sea level used in the analysis for performance period timeframes longer than 10,000 years but shorter than one million years. If the FEPs cannot be excluded, they should be included in the associated analyses, as described in Table 2-1.

Even on a qualitative level, the probability of future tsunami hazards for a particular location would be too difficult to estimate over the performance period. The level of effort required to evaluate future tsunami hazards is likely to be excessive and technical analyses is not warranted considering the short duration that a potential disposal site would be flooded by a tsunami.

<u>Flood Plains and Wetlands</u>

Flooding and additional water may impact the performance of a disposal system. Important aspects include: (1) the location of the current 100-year flood plains and wetlands in relation to the potential disposal site, and (2) how the current boundaries of the flood plains could change over the compliance, protective assurance, and performance period, if performance period analyses are required.

Flooding can directly influence the performance of the disposal system or trigger another process, such as erosion, that can impact the performance of the disposal system. Higher topographic areas generally have fewer floodplains and wetlands; the effects of erosion usually become problematic before flooding. On the other hand, depositional areas and relatively flat areas would have a potential of becoming flood plains and wetlands.

Knowledge of the past surface hydrology in the potential disposal area can be used to strengthen the qualitative FEP assessment. For example, the surface hydrology of southern Louisiana is quite diverse. The Mississippi River and other rivers have changed river channel beds numerous times and 100-year floodplains would change in concert with river course evolution. Disposal sites for significant quantities of long-lived waste should not be located in the vicinity of these channels.

Features and processes identified in studies of the past natural history of the area often provide an indication of what processes will likely be present in the future. If, for example, an area has been frequently flooded during and immediately after past glacial periods to create intermittent glacial lakes (e.g., Lake Missoula, Lake Lewis, and Lake Bonneville), the probability is high that similar processes and events will occur during the performance period.

Geomorphologic evidence may provide useful data on large paleofloods. The evidence can include slack-water deposits, scour lines, high-water marks, and undisturbed areas (Stedinger and Cohen, 1986). The advantage of paleoflood data is that it can improve a probabilistic flood hazard assessment and extend short or non-existent flood records to include the last 1,000 to 10,000 years (Klinger and England, 2013). Paleoflood data can improve the estimates of the magnitude and frequency of large floods. Licensees should develop an assessment of the potential for future flooding and for local floodplain and wetland formation in the future.

In addition, paleoflood data may provide evidence of large, dynamic floods, similar to the “outburst” floods that occur when the water of dammed glacial lakes are suddenly unobstructed. Such massive, violent floods could destroy a disposal site located close to the surface and thereby fail to meet the site stability performance objective (i.e., 10 CFR 61.44). Potential sites located in areas affected by previous glacial processes and/or subjected to previous massive flooding would require additional analysis and careful evaluation. Although the site and immediate area would not be habitable for humans and a potential receptor, the contaminated material may remain in a relatively concentrated form while being deposited downstream near more habitable locations where receptors could exist. Potential disposal sites located in areas subject to previous massive flooding may require deeper disposal and additional man-made barriers (e.g., engineered surface covers) to mitigate the destructive force of large floods.

> **10 CFR Part 61.50(a)(2)(iii)**: *The disposal site must provide sufficient depth to the water table that groundwater intrusion, perennial or otherwise, into the waste will not occur. The Commission will consider an exception to this requirement to allow disposal below the water table if it can be conclusively shown that disposal site characteristics will result in molecular diffusion being the predominant means of radionuclide movement and the rate of movement will result in the performance objectives of Subpart C of this part being met. In no case will waste disposal be permitted in the zone of fluctuation of the water table.*

A potential site located in an area with a relatively large number of wells and data on groundwater fluctuations should be sufficient for a licensee to perform FEP screening associated with depth to water table. An area without sufficient data on the local water table and associated groundwater fluctuations may need additional site characterization. Features of interest for a licensee are current water table elevation and soil types, including sediment layers, with the potential for creating a perched water zone. A licensee should identify the hydrogeologic units of the layers below the disposal site. For example, a caliche layer or dense clay may cause temporary perched zones that may only exist on a seasonal basis. It should be sufficient for a licensee to identify such features in combination with meteorological data, topography of the disposal system, and processes of the local hydrogeology in their analysis of current water table behavior.

The requirement at 10 CFR 61.50(a)(2)(iii) is closely related to the requirement at 10 CFR 61.50(a)(2)(i) (i.e., poor drainage and flooding). Future water table elevation is partially a function of the current landscape and potential changes to the landscape in the future. As with the requirement in 10 CFR 61.50(a)(2)(i), topography, hydrogeology, erosion rate, and precipitation rates are determining factors for water table elevation. With updated studies on long-term trends, past natural history, and PMP/PMF, it should be possible for a licensee to develop an assessment to bound potential water table changes. Water tables in topographic highs or steep areas may have a greater degree of seasonal variability, but generally would be expected to have a smaller potential to significantly change during the long term than would a relatively flat, depositional area that is susceptible to drought and flooding. Depending on the hydrogeology of the region, a low-lying or depositional area today can experience a rising water table or even become a flood plain in a future wetter climate.

A number of tools and codes are available to licensees to support analyses and assessments of groundwater discharge that can be used to assist in making a determination regarding long-term water table fluctuations. Knowledge of the paleoclimatolgy, paleopedology, and past hydrology of the potential disposal area can support the assessment of this requirement. For example, arid regions with wetter conditions in the past may have had higher water tables, but never close enough to the surface to have posed a threat to a potential future disposal site. However, evidence of the past has revealed that features such as wetlands and lakes had previously existed in currently arid areas. Death Valley is a good example: generally dry and waterless, this valley had been flooded in the past (Lake Manly) and was persistent enough to support a native population. Death Valley is currently dry because of the extremely low rate of precipitation at and near the area. However, a geomorphologist, or a qualified specialist, would recognize that its topography is ideal for lake formation, if more water were to become available (as evidence from its geological past has shown). Other areas may receive a high rate of rainfall, but the topography and geology will not allow for lake formation in the future.

In general, the climatic history during the Quaternary period has been of a cyclic nature consisting of glacial and interglacial stages. Features and other evidence of the past natural history can assist in reconstructing the full cyclic climatic history including precipitation rate and temperature ranges. Potential disposal sites further to the south may never have experienced glacial coverage in recent geologic history. Knowledge and evaluation of the full cyclic extremes, and updated studies of topographic trends (e.g., surface uplift, tectonic subsidence, erosion vulnerability, etc.), can help a licensee in developing an assessment that could potentially bound long-term water table fluctuations, even if these fluctuations may have been extreme. Potential disposal sites further to the north may have been previously covered by glaciers that cause disruptive surface geologic processes so that the requirement 10 CFR Part 61.50(a)(4)(iv) becomes the primary focus.

> **10 CFR Part 61.50(a)(2)(iv)**: *The hydrogeologic unit used for disposal shall not discharge groundwater to the surface within the disposal site.*

The criterion in 10 CFR 61.50(a)(2)(iv) is closely related to the criterion in 10 CFR 61.50(a)(2)(i) and 10 CFR 61.50(a)(2)(iii). Groundwater discharge areas are partially a function of the current landscape and any potential changes to the landscape in the future. As with the requirement in 10 CFR 61.50(a)(2)(i), topography, hydrogeology, erosion rate, and precipitation rates are determining factors if water will discharge in a certain area. Any time a water table rises higher than the ground surface, groundwater will discharge to the surface. The assessment done for 10 CFR 61.50(a)(2)(iii) should assist in determining if the hydrogeologic units used for disposal are able to discharge groundwater to the surface within the disposal site under current or projected future conditions. A licensee should compare the approximate rise and fall of the water table assessed in 10 CFR 61.50(a)(2)(iii) to the changes in topography.

Different combinations of trends should be considered by licensees: net mass change (deposition/erosion) and net change on water table (rising/falling). For example, it is possible that areas with relatively stable long-term water table levels may also experience relatively high erosion rates; the net effect is a water table advancing to the ground surface. It is unlikely, however, that such sites would fulfill the requirement of 10 CFR 61.50(a)(4)(iv) which states that areas with significant surface geologic processes must be avoided. Site characterization should provide sufficient data to a licensee on geology, hydrogeology, topography, paleoclimates, and features and processes to qualitatively assess the plausibility of groundwater discharge occurring sometime in the future. Evidence supporting the existence of past groundwater discharge areas, such as calcite deposits or diatomite, vastly increases the chances that the disposal area will have groundwater discharge occurring during the analyses timeframes.

> **10 CFR Part 61.50(a)(4)(iii)**: *Areas must be avoided where tectonic processes such as faulting, folding, seismic activity, or volcanism may occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of Subpart C of this part, or may preclude defensible modeling and prediction of long-term impacts.*

Tectonic processes, such as faulting, folding, seismic activity, and volcanism, are processes that might lead to short disruptive events, but unlike the processes associated with other disposal site suitability requirements, these processes are linked with plate tectonics that proceed at very slow rates. The assessment and evaluation carried out for the compliance and protective assurance periods to approximate the frequency and extent of faulting, folding, seismic activity, and volcanism in a particular area, as discussed in NUREG-1200, should not lead to significantly different results when applied to the performance period. These are long-term processes and unlike the processes related to the previously discussed site suitability requirements, water is not directly involved. Tectonic processes are large-scale processes and the frequency and extent of seismic and volcanic activity will not vary much when extrapolated to the performance period. The licensee should conduct a thorough assessment of 10 CFR 61.50(a)(4)(iii) based on the guidance in NUREG-1200 and NUREG-1199.

> **10 CFR Part 61.50(a)(4)(iv)**: *Areas must be avoided where surface geologic processes such as mass wasting, erosion, slumping, landsliding, or weathering occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of Subpart C of this part, or may preclude defensible modeling and prediction of long-term impacts.*

FEPs that could cause changes in the frequency and extent of the surface geologic processes are climate, topography, geology, soil type, type of flora, water chemistry, and the matrix in which the water flows. Short-term, large-scale topographic change normally does not occur unless associated with a disruptive event. The frequency and extent of water (i.e., precipitation rate) has the greatest potential for driving rates of mass wasting, erosion, slumping, landsliding, or weathering. NUREG-1623 provides guidance on surface geologic processes. FEPs that could cause unsuitable rates of erosion include increased rainfall and/or an increased gradient (and therefore, an increase in the erosional power of any runoff). As for the increased precipitation, the magnitude of the PMP/PMF is not likely to change significantly in a wetter climate, based on the conservatism associated with the estimation of the PMP.

A licensee can use technical assessments to assist in estimating the rates of surface geologic processes and determine if the FEP should be included in the analyses. The field of geomorphology has evolved significantly over the last half century and numerous technologies are available today to facilitate studying surface geologic processes including various programs such as hydrologic codes, erosion codes, and landscape evolution codes (e.g., CHILD and SIBERIA). Section 5.0 provides more detail on the technical assessment of erosion. Landscape evolution is especially important with respect to potential changes to nearby streams and river channels in unconsolidated material. Given sufficient precipitation, large rain events, and time, the watershed of an area can change considerably. Specific parts of a facility may end up close to stream channels and with an increased gradient. Drainage patterns may change if variations in climate circulation patterns are great enough. Erosion/deposition rates may vary spatially and temporally across the site. Long-term erosion often concentrates in gullies which do not uniformly erode over their entire length. Peak erosion depth may translate into a total breach of a portion of the disposal facility.

The massive ice covers of the glacial periods were a source of extensive, large-scale surface geologic processes. Figure B-9 shows the approximate area covered by glaciers during the last three glacial periods of the current Quaternary ice age (i.e., the Wisconsin, Illinoisan, and Pre-Illinoisan glacial periods). Glaciers can cause very disruptive surface geologic processes, and potential sites located in areas affected by previous glacial processes could require additional analysis and careful evaluation.

Evidence of the past natural history of the area, or from an appropriate natural analog, should provide support to licensees for excluding, or retaining, the FEPs associated with the surface geologic processes. Pedogenic processes, biotic activities, and bioturbation are all processes that may impede or accelerate surface geologic processes. Thick root systems from certain plants are known to greatly reduce the erosional force; however, it is difficult to rely on the continuous presence of a specific plant that might be needed for longer timespans. Any number of factors could influence flora such as drought, fire, disease, fungi, and insects.

2.5.3.1.2.2 Probability

Licensees use screening criteria, based on the probability of occurrence and/or consequences to the performance of the disposal system, to screen out FEPs that are unlikely to occur or that have relatively minor consequences. Three methods that a licensee may consider that handle probability depending on the extent of quantification of the FEPs concerned include (EC, 2009a):

- *Quantitative methods*, where all FEPs are represented numerically and event probability is an explicit part of the performance assessment calculation, such as those methods employed in the probabilistic models used for the Yucca Mountain and Waste Isolation Pilot Plant projects. For example, a performance assessment required by 10 CFR Part 63 should not include consideration of very unlikely FEPs (i.e., FEPs that are estimated to have < 1 chance in 10,000 within 10,000 years of occurring). As a result, FEPs with probabilities lower than 10^{-8}/yr should be screened out during the scenario development process. The probability classification in its entirety would include the following and could be used in conjunction with the qualitative approach as points of reference:

- Implausible: Very Unlikely (<10^{-8}/yr)
- Plausible: Unlikely or Less Likely (<10^{-5}/yr and >10^{-8}/yr)
- Plausible: Reasonably Foreseeable (>10^{-5}/yr or >1 chance in 100,000 per year or about a 1 in 10 chance of occurring over a 10,000 year period)

- *Qualitative methods*, where the probability or likelihood of occurrence of FEPs is described qualitatively or semi-quantitatively, and probability values are not an explicit part of the numerical modeling. However, a qualitative description of probability could still be used (e.g., unlikely vs. very unlikely). Qualified specialists would need to determine the level of probability, as well as the terminology to be used to describe that probability. For example, experts on paleofloods may determine that a site's physical environment and topography preclude major flooding. The low probability from this qualitative determination could then be labeled as either "very unlikely" or "implausible" or some other term depending on the terminology agreed upon. The level of effort for this method is appropriate for LLW disposal sites and is recommended for the analysis of FEPs.

- *Non-consideration of probability,* especially where few or no relevant data are available and there are large uncertainties associated with describing the scenario. With this method, FEPs are included as a result of lack of information.

One technique applicable to FEPs screening based on probability is the frequentist technique (EC, 2009b), where probabilities are based on observations on how often a phenomena has occurred at the proposed site or at a natural analog to the site. Constraints to using this technique include limited data or non-representativeness of the data that is available.

<u>Uncertainty Associated with Probability</u>

The main consideration in the assignment of probabilities to scenario-forming FEPs is credibility. This area of the FEPs analysis relies on the skills and experiences of the analysts and on the qualifications of the independent reviewers. Most probability estimates developed by licensees will include a substantial amount of judgment. Because the FEP screening process can result in FEPs not being further considered in the analyses, licensees should make conservative decisions when screening based on probability. Probability screening will involve the use of existing data in areas like paleoclimatology, plate tectonics, hydrology, geology, and natural resources coupled with expert judgment. It is important that the estimates are documented.

When there is sufficient and reliable information available, an analyst can have confidence in probability estimates and the understanding of uncertainty in the probability estimates. If the sampled population on which the probability is based is small or the quality of the data is poor, or if the estimates are based on assumptions, then the uncertainty associated with probability can be high. As previously discussed, long-term analyses or estimates may be more difficult to quantify due to an increasing scarcity of reliable data. The probability of occurrence for an earthquake above a certain magnitude over a 100-yr. period would be uncertain however the confidence in the probability estimate may be relatively high when compared to the uncertainty in the probability of tundra-like conditions occurring at a particular location many thousands of years in the future. When using probability to screen FEPs, the uncertainty in the probability must be taken into account.

2.5.3.1.2.3 Consequence

Many of the same characteristics and difficulties associated with quantifying probabilities also apply to attempts to quantify consequences or impacts on disposal site performance. A conservative semi-quantitative approach is generally better suited than a quantitative approach when using consequence as a screening criterion. For example, a bounding consequence calculation could be, under the appropriate conditions, a helpful conservative calculation to indicate that the associated impact will be insignificant. One problem with consequence screening is that as the technical analyses becomes more complex, the output from the analyses may become more complex and less intuitive, making it difficult to screen based on consequence without performing a quantitative analysis. Shelf- and cliff-type responses, as well as local minima and maxima, can confound interpretation of bounding consequence or other types of significance determinations. Example 2.4 provides an example of a cliff-type response and the way it may affect FEP screening.

Example 2.4: A good example of a cliff-type response is the transport of a short-lived, sorbing radionuclide. At high values of the distribution coefficient, the radionuclide decays in place. However, at low values of the distribution coefficient, the radionuclide may be transported to a potential receptor location. A measure of the central tendency of the distribution coefficient distribution may inappropriately show that the radionuclide poses little risk even though a small change to the sorption coefficient would allow the radionuclide to arrive at the receptor location during the compliance period or protective assurance period and potentially cause a significant consequence.

A performance assessment model will commonly have inter- and intra-dependent components or submodels. For this reason, the initial development process should err on the side of including FEPs of unclear significance. Once the model is developed and the connection and communication of submodels have been established, then the significance determination process can more reliably eliminate FEPs.

The inclusion or exclusion of a FEP in a performance assessment model depends on whether it has a measureable, observable, or significant effect on disposal system performance. Since FEPs are not measurable or observable in the far future, expert judgment will constitute a key element of the screening process. Experts or specialists would need to determine the magnitude of the consequence, as well as the terminology to be used to qualitatively describe that impact (e.g., significant, major, substantial). For example, if it is plausible that the consequence of a FEP can be expected to change dose results that are relatively close to the performance objective, then the impact of the feature or phenomenon in question is significant. In addition, if the output results change by orders of magnitude depending on the absence or presence of a feature, or the occurrence or absence of a phenomenon, then the impact of the feature or phenomenon is significant. Previous performance assessments may provide insights to consequence, or additional modeling or sensitivity analyses could assist in determing the impact. Depending on the complexity of the system, this process may need to be iterative.

Since subsystem-level effects on system-level performance may be masked by certain designs and/or combinations of input parameter values, the quality of the FEP analysis relies on the qualifications and judgment of the analysts. In addition, the licensee using consequence-based FEP screening should consider the interrelationships of the FEPs with one another, and the effect different combination of FEPs may have on the consequence (e.g., if an engineered surface barrier cover is performing as planned, the performance of other engineered features may be masked for a specific period of time).

Uncertainty Associated with Consequence
When there is sufficient and reliable information available, an analyst can have confidence in consequence estimates and the uncertainty may be low. If there is limited information, the quality of the data is poor, or if the estimates are based on assumptions, then the uncertainty associated with consequence may be high. In addition, if qualified specialists have difficulty determining masking effects, the uncertainty associated with consequence estimates can be high. As previously discussed, the interrelationships of the FEPs with one another, and the effect different combinations of FEPs may have on the consequence should be considered to the extent possible. For example, variable temperature and chemical composition of groundwater may affect the rate of radionuclide transport. Distribution coefficient (K_d) values for radionuclides may also change due to the changing environments. However, these different FEPs (inherent groundwater variability vs. temporal variability in the environment) may affect the K_d values for individual radionuclides in opposite ways. In other words, it may be challenging to determine the consequence of a single FEP when many FEPs are uncertain as to their influence on the results. High uncertainty in the consequence of a FEP should result in the FEP being included, unless even with the uncertainty the FEP can be shown to not likely to be significant or the timing of occurrence will be delayed outside of the regulatory analysis timeframes.

2.5.3.1.2.4 Screening Techniques

Although there may be different ways to organize, evaluate, and present the FEPs, most methods have certain similarities and the lists of retained FEPs obtained by different methods should be similar. Techniques are not mutually exclusive and licensees may use several tools in combination. The following section outlines one systematic screening technique, but there may be other valid techniques that a licensee may use.

Systematic FEPs screening by licensees will involve the use of professional judgment. Screening criteria matrices categorize phenomena into various elements according to the magnitude of the probability and the consequence (Hommel, 2012; NEA, 1992). For example, Table 2-2 illustrates the approach of using a combination of probability and consequence of a FEP, in conjunction with the uncertainty associated with that FEP, to retain or screen out the FEP (IAEA, 2004). Screening criteria matrices require specialists and experts to select the FEPs they estimate to be important and include in the assessment. Screening criteria matrices are one method that can provide transparency. Table 2-2 presents an example matrix that licensees can use to perform FEP screening for a LLW disposal facility performance assessment. Factors used for initial screening purposes include (1) probability of the FEP, (2) consequence of the FEP, and (3) the uncertainties associated with the probability and consequence.

Depending on the probability, a phenomenon or feature can be placed either below or above a screening value as seen in column 2 of Table 2-2. FEPs can be screened in or out if a qualitative screening limit is selected and applied. For example, analysts may decide that FEPs with “very unlikely” probabilities should be screened out while FEPs with an “unlikely” probability should be included in the scenario development. The third column divides the uncertainty associated with the probability into high and low uncertainty. Consequence is handled in a similar manner as probability, which can be seen in columns 4 and 5 in Table 2-2. Analysts can assign a qualitative consequence screening limit in addition to an uncertainty estimate associated with the consequence. After being evaluated, a FEP will have assigned designations for the probability, consequence, and their uncertainties. Based on these designations, the qualified specialists will screen FEPs in or out, as shown in the far right-hand column.

Table 2-2 Example of Screening Criteria Based on Qualitative Probabilities, Consequences, and Uncertainty Associated with a FEP

Case	**Probability** Below a Qualitative Screening Limit - e.g., "very unlikely"	**Uncertainty** Associated with Probability	**Consequence** Below a Qualitative Screening Limit – e.g., "not significant"	**Uncertainty** Associated with Consequence		**Screening Outcome**
1	yes	low	yes	low		Out
2	yes	high	yes	low		Out
3	yes	low	yes	high		Out
4	yes	high	yes	high		In [Out*]
5	yes	low	no	low		Out
6	yes	high	no	low		In
7	yes	low	no	high		Out
8	yes	high	no	high		In
9	no	low	yes	low		Out
10	no	high	yes	low		Out
11	no	low	yes	high		In
12	no	high	yes	high		In
13	no	low	no	low		In
14	no	high	no	low		In
15	no	low	no	high		In
16	no	high	no	high		In

* Screening outcome for the protective assurance period if not part of the compliance period

Whether a FEP is screened in or out is apparent in most of the 16 cases in Table 2-2. For example, in case 1, a FEP is clearly screened out since both probability and consequence are below a screening limit and their associated uncertainties are small. Conversely, FEPs in cases 13-16 are retained for scenario development despite the various degrees of associated uncertainty since probability and consequence are both above their screening limits. Some of the cases are not as straightforward and are worth discussing in more detail below.

For cases 2 through 4, cases 2 and 3 have probability and consequence below predetermined, qualitative screening limits. For case 2, the uncertainty associated with consequence is low and for case 3, the uncertainty associated with probability is low, giving the analyst sufficient confidence to exclude the FEP from further consideration. For case 4, there is less confidence since both probability and consequence have a high uncertainty associated with them and although probability and consequence are below screening limits, the uncertainties associated with both probability and consequence would lead the analyst to keep the FEP for scenario development during the compliance period.

Cases 5 through 8 all have consequences above the screening limits indicating potential inclusion of FEPs for further consideration; however, the uncertainty associated with the probability is important to determining their final inclusion or retention. If there is low uncertainty associated with a probability lower than a screening limit, there is confidence that despite the higher impact or consequence, the probability of its occurrence is sufficiently unlikely so that the FEP could be screened out (cases 5 and 7). Whereas, if there is high uncertainty associated with the small probability, as in Cases 6 and 8, the FEP should be screened into the analysis.

Cases 9 through 12 are the converse of cases 5 through 8; all cases have probabilities above the screening limits indicating potential inclusion of FEPs for further consideration. However, if there is low uncertainty associated with a consequence lower than a screening limit, there is confidence that despite the higher probability of the FEP occurring or being present, the impact of the FEP is sufficiently insignificant so that the FEP would be screened out (cases 9 and 10). Whereas, if there is high uncertainty associated with the small consequence, as in Cases 11 and 12, the FEP should be screened into the analysis.

Increased uncertainties associated with the phenomena and features of the protective assurance period compared to the compliance period would be reflected in the potentially increasing number of FEPs and the uncertainties associated with probabilities and consequences of the FEPs. As a result, a larger number of FEPs may be retained based on this increasing uncertainty. However, FEPs from the protective assurance period with probabilities and consequences that are <u>both</u> below their respective screening limits should be screened out and not included in any scenarios for the protective assurance period if they have not already been included in the compliance period analysis. For case 4, both probability and consequence are associated with high uncertainty, although both are below screening limits. For the compliance period, the uncertainties associated with both probability and consequence would lead the analyst to keep the FEP for scenario development. If the FEP continues to be present or occur during the protective assurance period, this FEP would be part of the scenario development for this period. However, if a FEP is new to the protective assurance period and not a feature or phenomenon of the compliance period, the FEP would not be part of the scenario development for assessment for that period (see far right-hand column in case 4).

A licensee may extend compliance period calculations into the future without modification, provided that the calculations are complete with respect to including key FEPs relevant to the protective assurance period or excluding FEPs only relevant to the compliance period. However, since the protective assurance period is considerably longer than the compliance period, FEPs that have been excluded from further consideration in the compliance period may not be able to be screened out from further consideration for the protective assurance period analyses. Potentially significant FEPs may need to be considered during scenario development if disruptive processes are expected to start occurring during the protective assurance timeframe or if the cumulative impact from repetitive events over the longer timeframes is not included and the repetition of those processes and events could lead to significant impacts.

2.5.3.2 *Top-Down Approach*

The concept of safety functions has been used with increased frequency due to recent work on scenario development methodologies (EC, 2009b). An advantage of the top-down approach includes focusing on the capabilities of the significant barriers and considering behavior of individual features in the context of overall system performance relative to the decision to be made. Some consider the top-down approach a simpler way to develop scenarios since safety functions are more quickly identified than significant interrelationships between FEPs and since the probabilities of the resultant scenarios may be easier to estimate. Since the discussion below only provides a brief description of this approach, licensees may refer to the sources given in the reference section (Section 12.0). As previously stated, both the top-down approach and bottom-up approach are often used simultaneously in a complementary way.

2.5.3.2.1 Safety Assessment and Safety Functions

Safety assessments are a systematic analysis of the ability of the site and design to provide the safety functions and meet technical requirements. A safety function is defined qualitatively as a role through which a component of the disposal system contributes to safety. Safety functions are the diverse capabilities and components of the barriers found within a disposal system that are used to reduce the potential for the release of radioactive material and to ensure that any releases are within acceptable limits. The safety functions may differ as the time period changes. For example, the capabilities of a surface cover component may be relied upon to achieve short-term safety objectives for a LLW disposal site while the long-term capabilities of the wasteform itself may be relied upon for the long-term safety functions. Analogous to the use of a fault tree analysis for nuclear reactor safety (NEA, 1992), knowing when a safety function is expected to be available and when it can be relied upon will affect scenario development.

A safety assessment and the findings of the safety assessment are essential components of the collection of arguments and evidence in support of disposal system safety. Other components supporting the safety of a radioactive waste disposal facility should include:

- A description of the waste and the rationale for the chosen waste management strategy;
- Descriptions of the disposal concept, the disposal facility, the disposal site and it's safety functions;
- Description of the management system applying to the different phases of facility development; and
- Any other information that support continued development, operation, and closure of the facility.

Relevant examples of the top-down approach to developing scenarios include HLW disposal facilities. Due to the relatively recent development and application of the approach for LLW disposal (EC, 2009b), less examples exist for LLW disposal since performance is more focused on the relatively active near-surface geomorphology than on the more passive deep geology. The top-down approach is similar for both LLW disposal and HLW disposal, although less effort is expected to apply the approach to LLW since the level of effort (i.e., the level of detail, comprehensiveness, completeness, and degree of iteration), is commensurate to the longevity, concentrations of radionuclides, and quantity of the waste.

2.5.3.2.2 Safety Functions and Scenario Development

A number of organizations that have developed performance assessments for waste disposal develop scenarios using a top-down approach to FEPs. Some national programs link FEP records with statements about safety functions (e.g., by specific tools such as FEP charts (SKB, 2006)). Uncertainties in the performance of systems may give rise to scenarios. A licensee can identify plausible, alternative scenarios when safety functions are no longer expected to perform as intended. The aim of the scenario development process is to identify deviations from an expected evolution scenario, based on the failure of one or more safety functions or the extent or form of degradation of one or more safety functions. The main safety functions are associated with the engineered barrier system and the barriers of the natural system. In the scenario development process, a licensee can develop altered evolution scenarios by considering the timing of FEPs, their consequences in terms of safety function effectiveness, and the status of other safety functions. There is generally no safety function assigned to the biosphere.

The proposed methodology for scenario identification consists of six steps (EC, 2009c):

1) Define a set of safety functions associated with the engineered and natural barriers for the considered disposal system.
2) Develop a safety concept based on the functioning of the disposal system in the case of the central scenario. This is strongly directed by the question "when is a safety function expected to be available or when can it be relied upon."
3) Build a structured set of safety statements. These statements are derived from the requirements on the disposal system, on the sub-systems and on individual components.
4) Make a systematic analysis of the uncertainty affecting the safety statements.
5) Identify a list of possible altered evolution scenarios by considering all identified uncertainties and by testing if they have the potential to propagate to higher level statements, and eventually to affect the safety functions.
6) Derive a final set of altered evolution scenarios. This is done by constructing functional diagrams illustrating the impact of the considered uncertainty in a safety statement on the functioning of the disposal system and by grouping, as far as possible, scenarios with identical or strongly similar functional diagrams.

Structuring and identifying safety-relevant phenomena, information, and uncertainties is a prerequisite for scenario formulation using a top-down approach. The starting point for the identification of safety-relevant phenomena and uncertainties is the development of a detailed description of the initial state of the system and its subsequent evolution. Several tools have been developed and applied, including system-specific FEP databases, interaction matrices, influence diagrams, assessment model flowcharts, phenomenological analysis of the disposal system, storyboards, timeline with subdivision of timeframes, and process description reports. Further information can be found in NEA (2012).

2.5.4 Constructing Scenarios

A licensee may evaluate multiple scenarios to evaluate scenario uncertainty. Although a licensee can never eliminate the uncertainty altogether, the technical assessment is an attempt to constrain the uncertainty associated with future events and processes. The following section outlines possible methods a licensee may use. There may be other valid techniques a licensee may consider. Appendix D provides additional information on techniques that may be useful.

The output of scenario construction is a set of scenarios encompassing most of the plausible future system states and their potential impact. Scenario development should not be done in isolation from the rest of the technical analysis process because it is influenced by and uses information from previous modeling and consequence calculations. The method a licensee uses for developing and selecting scenarios should be a traceable, structured, and transparent. A licensee should document and describe the method they have used to identify scenarios and the technical bases for choosing which scenarios are considered plausible. The licensee should justify that relevant processes and events have been identified and that future evolutions of the disposal system have been considered in the development of the scenarios.

Scenarios are often assembled and classified based on their likelihood of occurrence and on the probability of the FEPs comprising the scenarios. As introduced in Section 2.5.1.1, scenarios may be categorized based on their perceived likelihood of occurring. Common terms are defined below:

- The central scenario represents the evolution of the disposal system within the expected range of uncertainty and in the absence of unlikely disturbances. For some sites, this may be the only scenario developed. The central scenario has also been referred to as a main, nominal, normal evolution, reference, design, or base case scenario.
- Altered evolution scenarios, or alternative scenarios, represent less likely, but still plausible, representations of disposal system evolution, and also describe how disturbances affect the evolution of the system.
- “What if” or residual scenarios are considered implausible scenarios. They explore the robustness of the system, such as complete failure of a barrier, without identifying a particular degradation mechanism.
- Stylized scenarios are typically associated with future human actions (e.g., intrusion) where few or no relevant data are available and where there are very large uncertainties associated with describing the scenarios.

A licensee should provide the terms used to describe the different types of scenarios in an assessment and clearly explain their purpose. Once the scenarios have been developed, a licensee should develop a conceptual model of the disposal system that can estimate the associated release, transport and exposure mechanisms (discussed in Section 2.6).

2.5.4.1 *Central Scenarios and Alternative Scenarios*

A licensee should use scenarios to describe the scenario uncertainty associated with the system. The central scenario is the expected evolution of the system; the alternative scenarios are less likely but cannot be eliminated by the licensee. Scenarios allow for the licensee to use a mixture of quantitative analyses and qualitative judgments. The selected scenarios should together provide an appropriately comprehensive technical description of the estimated performance of the disposal system.

Central scenarios are usually based on extrapolation of existing conditions into the future and incorporation of changes expected to occur in the future. The central scenario is considered to be the scenario best supported by available information and is usually considered to be a benchmark scenario against which the impact of alternative scenarios can be compared. The central scenario represents how the licensee expects the system to evolve assuming the proper functioning of the design with anticipated degradation. All of the significant features and processes that exist at a site should be captured by the central scenario. The central scenario is generally devoid of consideration of major events that change the future evolution of the site and the performance of the disposal system since most licensees will be selecting a potential disposal site where such events are not expected. It is acceptable for a licensee to treat anticipated future evolutions of the disposal system in one numerical model by varying parameter ranges. However, because the disposal system may evolve differently under alternative scenarios, it may be difficult to represent the different plausible FEPs all in one simulation model and additional models may have to be constructed.

Licensees should also develop plausible, alternative scenarios to investigate the impact of scenarios that are not expected but cannot be excluded. A licensee is not required to evaluate implausible alternative scenarios. However, there may be some utility for a licensee to evaluate sequences of events and conditions independent of probabilities, in order to illustrate the significance of individual barriers and barrier functions. In other words, the robustness of the disposal system can be examined. These alternative scenarios may represent less likely, but still plausible, modes of disposal site evolution (e.g., processes that impede the effectiveness of a feature important to waste isolation) as well as scenarios representing extreme natural events (e.g., earthquakes, volcanic activity, or glaciers) but that are still within the range of realistic possibilities within the analyses timeframe. Generally, a limited number of external FEPs will be of concern.

Various graphical and tabular techniques have been used to assist in scenario development (NEA, 1992; IAEA, 2004; NRC, 1995c; SKB, 2008). These techniques may be useful for a licensee to consider. These techniques include:

- Event trees, logic diagrams, and related approaches that analyze alternative combinations of events and/or of resulting system states
- Fault and/or dependency diagrams that set out in a hierarchical fashion the conditions and/or processes leading to, or contributing to, an end point of interest
- Influence diagrams that map the dependencies or interactions between various processes, often indicating the importance of the interaction
- Interaction matrices that force a comprehensive questioning of the dependencies between selected key features or processes
- Audit tables that force a consideration of the representation of each FEP within the available models and system representation, and evaluation of bias due to omission or simplified representation

- Judgmental approaches that rely on specialists in their field and expert judgment

The techniques listed above are not mutually exclusive and several tools may be used in combination. For example, influence diagrams and interaction matrices may be useful to explore and illustrate the connection between scientific understanding and the numerical models, whereas event trees and logic diagrams provide a logical structure for selection or generation of calculation cases. Whatever techniques are used, the judgment of analysts is critical to ensure that the scientific understanding is appropriately incorporated in the models. A key value of the graphical and tabular techniques is that they aid communication within projects enabling experts to see the significance of their knowledge within the system context. The techniques can also provide logical structure for the comprehensive documentation of the relevant processes and their representation in models.

2.6 Conceptual Model Development

A licensee should review the information provided by the assessment context, system description, and scenario development steps of the assessment approach and use it to develop a conceptual model of the site. The conceptual model of the site should qualitatively describe how the FEPs and significant barriers interact with one another and how the site functions. Licensees should describe any simplifying assumptions. Simplifying assumptions may be necessary when a licensee develops the site conceptual models. Regulators should review all simplifying assumptions and determine if adequate technical basis has been provided by the licensee. Simplifying assumptions typically involve the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical and chemical processes.

In order to identify areas that require more detailed consideration and reduce model uncertainty, an initial simple and conservative conceptual model could be developed based on limited data and design information. Further development of conceptual models by licensees should reflect an increased focus on significant radionuclides and processes. At all stages of the process, simplifying assumptions should be clearly identified by licensees. In any single conceptual model, the simplifying assumptions should be internally consistent and should also be consistent with existing information. Licensees should justify simplifying assumptions based on the current level of understanding of the system (NCRP, 2005).

For the scenarios that are to be quantitatively assessed, the conceptual model should be amenable to mathematical representation. The conceptual model should have enough detail to allow mathematical models to be developed to describe the behavior of the system and its components. Conceptual models developed by the licensee provide the framework for the computational models. It is important that the conceptual model is transparent and supported with adequate technical basis. More than one conceptual model may be consistent with available information. Appendix D provides additional information on techniques that have been used to develop conceptual models. If the set of alternatives does not represent the full range of possibilities, conceptual model uncertainty will be underestimated.

NRC (2003b) discusses conceptual model uncertainty and some of the most important activities on developing alternative conceptual models to reduce model uncertainty, which include:

- Maximizing the number of experts involved in the generation of alternative conceptualizations
- Minimizing inconsistencies, anomalies, and ambiguities
- Articulating uncertainties associated with each alternative conceptualization
- Obtaining key data to support each conceptual model alternative
- Considering alternative representations of space-time scales and of each feature and process

A variety of approaches have been used to facilitate the development of conceptual models in a traceable manner. Three examples taken from IAEA (2004) are given below.

The “safety assessment comparison approach” relies on the expert judgment and experience of the analyst carrying out the assessment. The first step is to identify the key release, transport, and exposure media by reviewing the relevant FEPs associated with each scenario. The mechanisms by which the associated release, transport, and exposure may occur are considered for each scenario.

Two strategies can be used based on information derived from each scenario:

- The deductive strategy reviews how release events might occur and considers the possible transport and exposure mechanisms and the associated impacts;
- The inductive strategy analyzes the impacts, considers the exposure and transport mechanisms that might have caused the impacts, and the associated release mechanisms.

The “interaction matrix approach” for developing a conceptual model allows the graphical representation of system interactions through the use of formalized procedures but does rely on expert judgment and is data intensive. The approach starts with a top-down approach to dividing the system into constituent parts. The resulting matrix and the FEP list contents can later be audited against each other. Using the interaction matrix approach to facilitate conceptual model development has the advantage of allowing disposal system components to be included explicitly in the interaction matrix and analyzed in greater detail by creating one or more sub-matrices. The interaction matrix approach allows FEP interactions and pathways to be mapped, which is an important step in developing and defining a conceptual model and in the logical progression to a mathematical model. Moreover, the systematic process of examining how the system components relate to one another may help to identify new, previously unrecognized relevant characteristics of the system. When using the interaction matrix approach for developing a scenario, the convention is to allocate off-diagonal elements in the direction of contaminant migration. In this way, contaminant migration pathways and the associated exposure pathways and exposure groups can be traced and translated into the conceptual model.

The “influence diagram approach” for developing a conceptual model also allows the interaction between FEPs to be identified in a logical and systematic way. Advantages and disadvantages are similar to the interaction matrix approach, although the influence diagram generally contains more detail than the interaction matrix. FEPs are represented by boxes and interactions between FEPs are illustrated by arrows showing the influence direction. The number of arrows between two FEPs will be equal to the number of influences between them. Only direct influences should be represented in an influence diagram.

2.6.1 Alternative Conceptual Models

Licensees should adequately describe and document conceptual model uncertainties. The performance assessment documentation should provide the assumptions, limitations, and uncertainties of the models. Multiple representations of the system may be consistent with the available data. In general, licensees should select the conceptual models that best represent available data and associated uncertainty. However, when data are sparse, multiple conceptual models may represent the available data. In this case, licensees should select the conceptual model that provides the most conservative result, or additional data could be collected to reduce uncertainty and determine which alternative conceptual model provides the most realistic representation. All conceptual models do not need to be abstracted and evaluated, but all models that are reasonably consistent with available information should be considered. Reviewers should perform an independent evaluation of model uncertainty and consider whether more than one conceptual model should be evaluated, especially for complex sites.

2.7 Numerical Model Development and Assessment

The numerical model development and implementation process typically consists of representing the conceptual models and their associated processes in mathematical models, and using modeling software to develop numerical simulations of the mathematical models.

This section provides guidance on the development of numerical models including (1) specific information on model abstraction of the conceptual model in order for it to be represented mathematically; (2) *model integration*; and (3) interpretation of model results.

2.7.1 Numerical Models[4]

In general, licensees will rely on numerical or computational models to estimate the future performance of a disposal site. However, the implementation of mathematical models in computer codes may not be necessary in all cases depending upon the complexity of the analysis. Additionally, the analyses are intended to be iterative and the level of detail and effort involved in a particular iteration may vary depending on the phase of facility development and the level of knowledge about the disposal site. For instance, during siting of the facility, simple models may initially be used to screen candidate sites, whereas, more sophisticated models may be needed during licensing of sites with unique characteristics such as complex site engineering or natural features. Although specific computer codes may be discussed or referenced in this guidance, the NRC does not endorse the use of any particular code or modeling software package for analyzing the performance of a LLW disposal site.

This section discusses issues licensees should consider when developing numerical models. First, licensees should select a numerical modeling approach that can appropriately represent the site's conceptual model and implement the mathematical model. Second, licensees should ensure that the selected numerical model is developed with adequate QA/QC.

[4] For this document, the terms computational model and numerical model are used interchangeably. In addition, the terms computer code, program, and software are used interchangeably.

2.7.1.1 *Selection and Implementation*

Licensees should select a numerical modeling approach that can represent the significant components of the conceptual model(s) for the disposal site, including the site-specific FEPs. The numerical model(s) will express the conceptual model as one or more mathematical expressions (e.g., algebraic and/or differential equations) with a set of boundary and initial conditions that are then solved. In many cases, more than one mathematical formulation could appropriately represent a conceptual model. Further, the expressions may be physically-based or empirically-based depending upon the level of scientific understanding of the physical processes, information available to parameterize the equations, and the spatial or temporal scales that the expressions are intended to model.

Three approaches are often employed to solve the equations in numerical models: analytical, semi-analytical, and numerical. These methods are summarized here from IAEA (2004). Analytical methods provide exact solutions and can be computationally efficient; however, the methods are typically only available for simple equations involving homogeneous or uniform spatial domains (e.g., one-dimensional steady-state flow and transport with simple boundary conditions). Semi-analytical methods are more flexible than analytical methods for solving more complex problems (e.g., flow and transport involving multiple sources and sinks). Numerical methods often discretize the spatial and temporal domains into a finite number of compartments or increments and solve the equations by iteration, matrix methods, or some combination of the two. Numerical methods can include finite-difference, finite element, method of characteristics, random walk, and analytic elements. Numerical methods allow for consideration of spatial and temporal variability, complex geometry and boundary conditions, and dimensionality. However, numerical methods can be computationally intensive, require highly trained personnel and can introduce numerical errors.

In the documentation of the numerical models, licensees should include information regarding the following:

- the mathematical formulation
- model assumptions
- sensitivity to ranges of input data and coefficients
- consistency of the pathways in the numerical model with the pathways of the conceptual model(s)
- accuracy of the software to reflect the model’s mathematical formulation (discussed in Section 2.7.1.2)
- the correct representation of the process or system for which it is intended
- stability characteristics of the numerical methods employed in the model (discussed in Section 2.7.1.2)

Because long-term behavior of the disposal system is of particular interest for numerical models that estimate the performance of LLW disposal facilities, licensees should provide comparisons between theory and experimental results, field observations, and other supporting information that may involve interpretation and extrapolation. In cases where more than one mathematical formulation may be appropriate, licensees should document why a particular formulation is preferred to the discarded approaches and, importantly, the limitations of the selected approach. Licensees may also wish to consult Appendix I of Safety Guide No. GS-G-3.4 for information about controlling the numerical models for waste disposal facilities (IAEA, 2008).

Reviewers should evaluate the conceptual model(s) and the numerical models to ensure compatibility with the site conceptual model including the source-term, transport pathways, and receptor scenario. For example, numerical models designed for the onsite receptor scenario may not be appropriate for assessment of an offsite receptor scenario. Reviewers should also ensure that the assumptions in the numerical modeling are consistent with the site conceptual model and that any deviations will not significantly affect the ability of the numerical model to represent the conceptual model. Reviewers should investigate the sensitivity of numerical model calculations to variations in input ranges to ensure that the model is numerically stable over the range of input parameters for expected site conditions. The range of input parameters may be different for alternative scenarios compared to the central scenario.

Licensees may select available modeling software, commercially-available or otherwise, or develop codes or modeling platforms specifically for site-specific purposes. The modeling software may be proprietary codes, modified codes, and/or codes specifically developed for implementation of the chosen mathematical models. Modified codes and codes specifically developed for a site-specific application are referred to generically in this guidance as "user-developed" codes. The use of proprietary codes usually has the advantage that the codes have been previously developed and checked. Proprietary codes may have a history of application to a range of different analogous problems. In contrast, user-developed codes need to be developed and checked by licensees. However, they do have the advantage of being tailored to the needs of the specific problem to be addressed. In all cases, it is necessary for a licensee to consider the process of software design based on a given mathematical specification (IAEA, 2004). Licensees should ensure that the software used for the numerical models is in conformance with the active standards of the IEEE Standards for software development, quality assurance, testing, verification, and validation (e.g., IEEE Standard 730-2002, IEEE Standard for Software Quality Assurance Plans). Reviewers should be familiar with NRC's Software QA/QC guidance (i.e., NUREG/BR-0167, NUREG-0865) to ensure the licensee's QA/QC procedures for selection and development of numerical models are comparable. It is recommended that proprietary codes are peer reviewed by the appropriate technical community prior to use in a licensing decision; however peer review is not required. The pertinent regulator may need to perform this function. Further guidance on software QA/QC is provided in the following section.

2.7.1.2 *Quality Assurance*

Licensees may develop computer codes or may use available codes (e.g., previously developed or commercially available) to simulate the performance of the disposal site using the site conceptual model. An essential element of modeling software development and/or usage is quality assurance (QA). Quality assurance associated with the field of code development is reasonably mature; this section of the document does not attempt to provide detailed guidance on software development. However, the main elements of software QA are discussed here. As part of QA for software development[5], a licensee should develop documentation of:

(1) Software requirements and intended use

(2) Software design and development; the software development process (if used), should be planned, controlled, and documented.

(3) Software design verification; software verification should be planned, documented, and performed.

(4) Software installation and testing

(5) Configuration control

(6) Software problems and their resolution

(7) Software validation; planning should include validation methods and validation criteria.

More detailed documentation should be provided if the code or modeling software is developed by the licensee compared to if a well-established, commercially-available product is used. For additional information the reader can consider Sections 4.4 and 8.0 of NUREG-1854 as well as Appendix I of NUREG-1757, Volume 2, and Revision 1.

The following bullets provide the information a licensee should provide and a reviewer should evaluate with respect to numerical model development.

- Valid data should be used in the numerical model. The data used in the analysis should be traceable[6] to their sources through all calculations and data reductions.
- The data should have been obtained or qualified under an acceptable QA program (e.g., an NRC-approved QA program developed to meet the requirements of 10 CFR Part 50, Appendix B).
- The numerical model should be demonstrated to adequately represent the processes or systems for which it is intended.
- The software should perform intended functions, provide correct solutions, and not cause adverse unintended results.

2.7.2 Model Abstraction and Model Simplification

Model Abstraction

A licensee will need to abstract the conceptual models they develop in order to translate the concepts into mathematical terms. Model abstraction is the process of abstracting a conceptual model representing a dynamic site in the physical world into a mathematical model governed by equations which is implemented within a numerical model. It is the process of determining the level of detail that should be preserved in the overall performance assessment model (or intruder assessment model). Figure 2-5 provides the types of abstraction that may occur in the

[5] Steps 4 through 6 apply to application of commercially available or existing codes as well as to development of user-developed codes.

[6] Traceability is the ability to trace the history, application, or location of an item or like items or activities through recorded identification.

model development process. The example provided is for development of a performance assessment model. Figure 2-6 provides a representation of the development of a hydrologic model (process model) for use in a performance assessment. Various abstractions may occur at many different steps in the model development process. Model abstraction builds on insights gained from FEP development and scenario analysis. In a LLW performance assessment, several model abstractions typically support the overall assessment of a facility's ability to demonstrate compliance with the performance objectives. These abstractions usually include models of projected climate and infiltration, degradation of barriers, source term release, transport through environmental media, and potential exposures to a receptor in the biosphere. Section 3.3 of NUREG-1573 (NRC, 2000a) and Section 3.0 of this guidance discuss issues related to these model abstractions in the context of a performance assessment.

Several factors can affect the complexity of the models that a licensee may use. Some level of simplification is generally required in order to translate the concepts of a conceptual model into mathematical terms. This simplification can take several forms, such as:

- The simplification of the geometry or structure—for example, considering a transport medium to be homogeneous and isotropic
- The omission of processes and interactions—for example, neglecting kinetic terms in chemical reactions
- A reduction in spatial or temporal resolution

<u>*Model Simplification*</u>

Model simplification is similar to model abstraction but more closely tied to modifying numerical models and consists of simplifying a complex numerical model into a reduced numerical model that has fewer components and is quicker to run while still maintaining the validity of the simulation results. For example, it may be appropriate for a licensee to reduce the detail of a submodel (e.g., for waste release) for incorporation in a performance assessment model. The model simplification process should demonstrate that the detail that has been lost is not essential to the estimated performance, which can be difficult to do in complex models and when supporting information is sparse. In addition, the simplified model should be compared to the detailed model to show that the simplified representation is appropriate. This comparison should be performed for base case models as well as for alternative scenario models. A simplified "model" can be something as simple as a data value or lookup table. For example, use of distribution coefficients (K_d) for radionuclide transport is actually a simplification of much more complex phenomena. The process of producing simplified models can introduce uncertainties and biases.

It is important that a licensee should clearly document both model abstractions and model simplifications. A licensee may need to perform abstraction of the real world system into a mathematical model using an iterative process. It is useful for a licensee to factor in limitations of the computational platform during conceptual model development. However, it is not appropriate to limit the assessment to the capabilities of existing computational platforms. In some cases, a licensee may need to develop a new computational model in order to appropriately assess the problem.

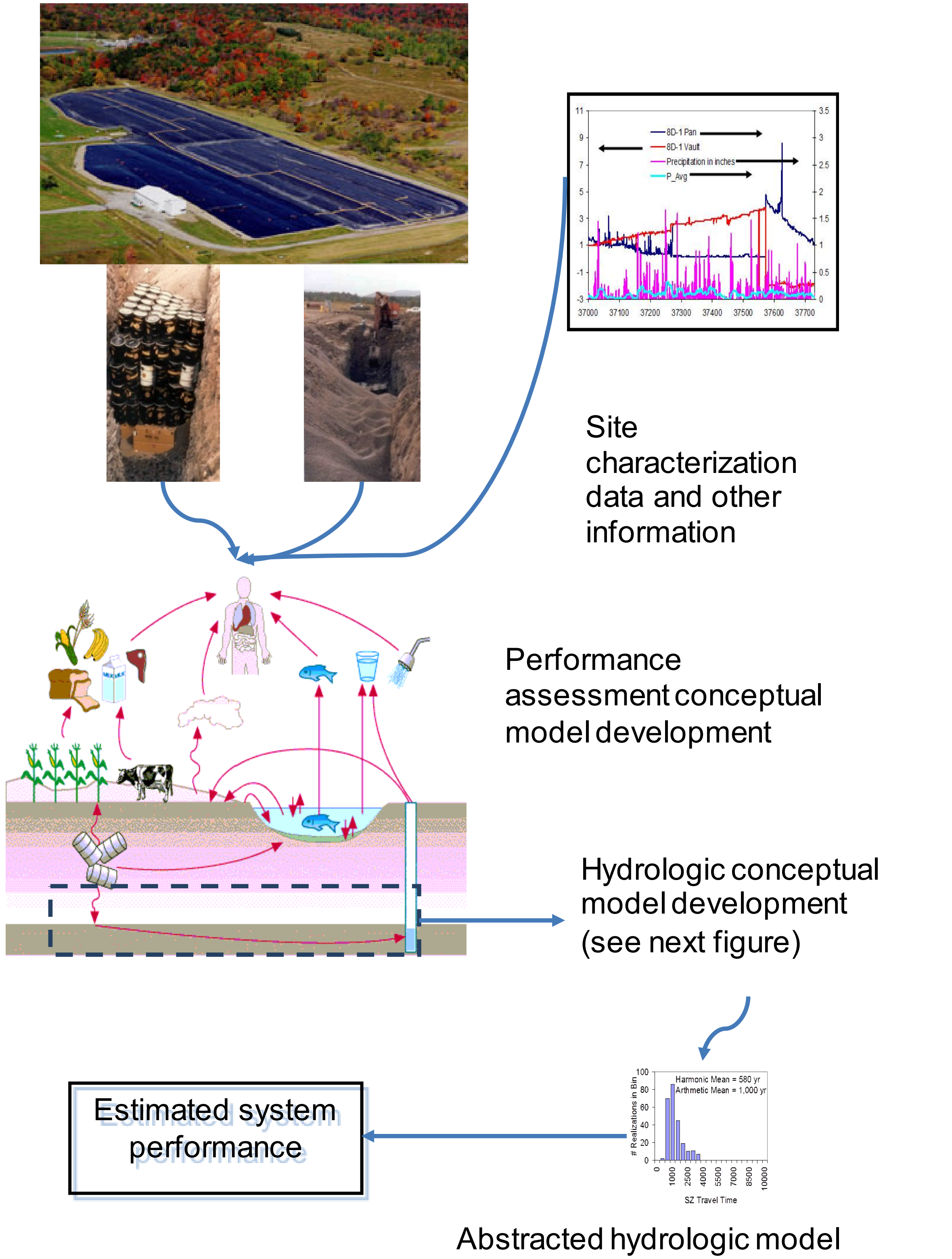
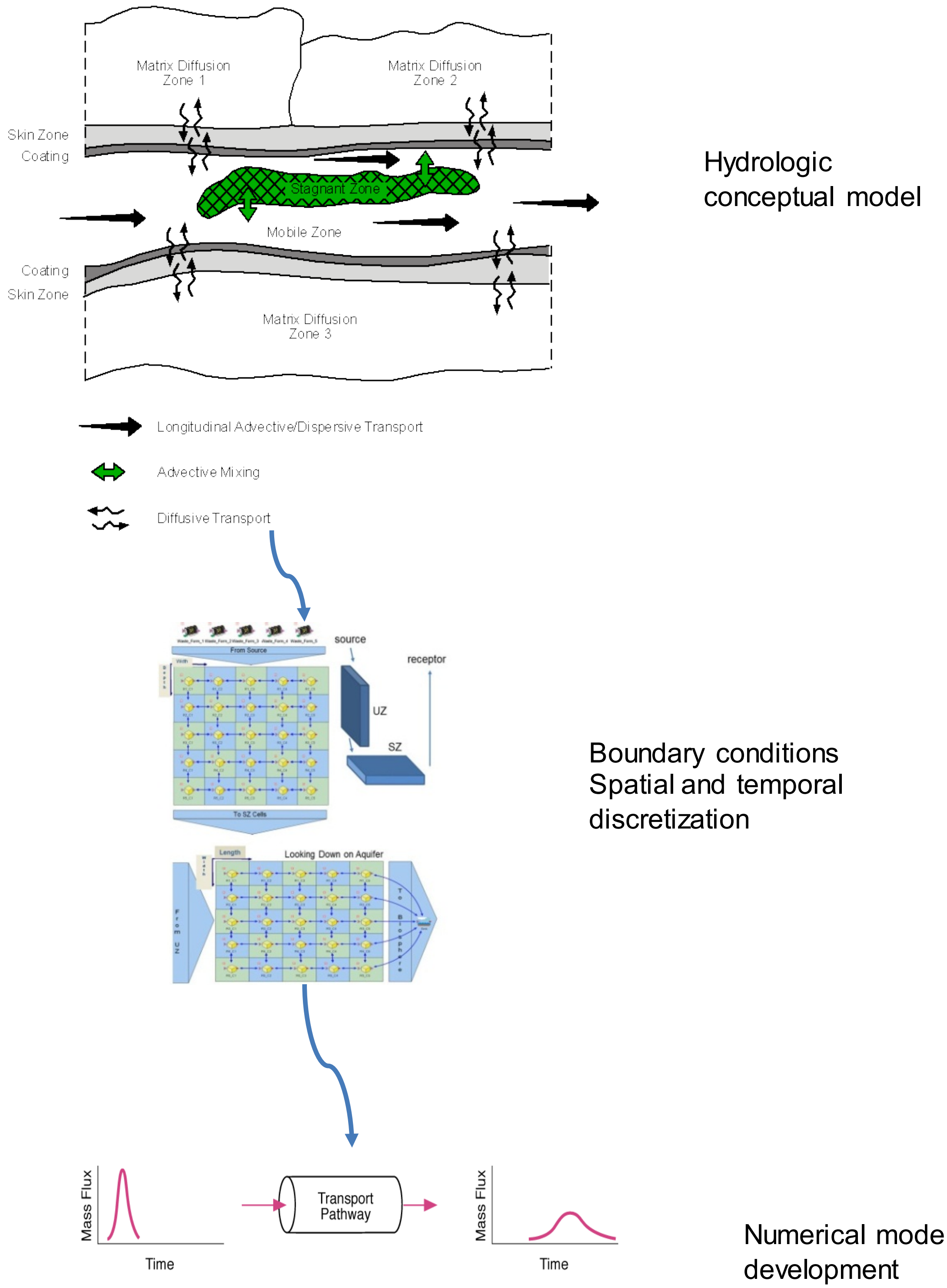


Figure 2-5 Overview of Abstraction as Applied to a Performance Assessment Model



$$m'_{is} = -m_{is}\lambda_s + \sum_{p=1}^{NPs} m_p \lambda_p f_{ps} R_{sp} (A_s/A_p) + \sum_{c=1}^{NCi} f_{cs} + S_{is}$$

Figure 2-6 Abstraction of a Hydrologic Model for a Performance Assessment Model

A natural tendency is to preserve all detail that may be developed in models supporting the performance assessment. However, this approach has disadvantages. The additional detail can make documentation, review, and understanding more difficult. In addition, many uncertainty analysis methods work better with a reduction in the number of inputs that do not affect the outputs. Model simplification should achieve a balance by preserving essential detail and eliminating unimportant detail.

2.7.3 Model Integration

The objective of the review of integration is to determine if the site and design description, data, parameter uncertainty, models, and model uncertainty have been appropriately integrated in the assessment. The reviewer should ensure that representations of the disposal system design and natural system features have been adequately integrated into the technical analyses. Assumptions, data, and models should be consistent throughout the technical analyses. Inconsistencies should be explained in the documentation or be corrected. Boundary and initial conditions should be consistent between different submodels in the performance assessment. Information that is passed between submodels should be verified to be of the appropriate temporal and spatial scale. If different models are used, information passed between models should be assessed to determine if unit conversions were made. Graphical representations can be useful to communicate integration in the technical analyses. Influence diagrams can be useful to document concisely the connections among submodels in the performance assessment.

2.7.4 Analysis and Evaluation of Results

Probabilistic approaches to performance assessment are preferred in most cases because they readily permit the propagation and assessment of the impact of uncertainty on the model results. However, use of a deterministic model to demonstrate compliance with performance objectives may be acceptable. In general, if deterministic modeling is used, it should be reasonably conservative, such that a subject matter expert, with minimal interaction with those who performed the assessment, could conclude that the analysis is conservative. Independent reviewers should evaluate the modeling in sufficient detail to be confident that the analysis is conservative.

For probabilistic analysis, the appropriate metric to use for comparison with the annual dose limits is the peak of the mean result. The peak of the mean is calculated by estimating the mean dose result over all probabilistic realizations, then taking the peak value of the mean curve. In some cases the mean curve may represent a high percentile of the projected output. Licensees may propose more conservative metrics; however, the NRC staff believes that the peak of the mean is protective.

If a probabilistic approach is used for the performance assessment, the reviewer will need to determine whether there is significant “risk dilution” affecting the calculation results. Risk dilution results when overly broad parameter distributions are selected primarily for processes that affect the timing of impacts. Although large uncertainty ranges may seem to be “conservative,” overly broad uncertainty ranges can artificially depress the peak of the mean dose result. For example, selection of an overly broad range for the K_d for neptunium-237 in the saturated zone may result in the estimated time of arrival of the contaminant at a receptor location being artificially spread over the period of performance, thereby "diluting" the risk at any one point in time.

For modeled processes and input parameters that are highly uncertain and cannot clearly be established as conservative, sensitivity analyses are necessary to establish the relative importance of these processes and parameters to the performance assessment dose calculations. NUREG-1757 (NRC, 2006; Volume 2, Appendix I, Section 1.7) and NUREG-1573 (NRC, 2000a; Section 3.3.2) summarize different methods for sensitivity and uncertainty analyses. Sensitivity analyses may identify the need for additional site characterization to adequately support the technical analyses.

Key parameters for further evaluation in a *sensitivity analysis* may be selected with a variety of different approaches, and the appropriateness of the approaches depends on the problem. It is anticipated that the sensitivity analysis and the performance assessment overall may be an iterative process. The initial approach evaluated may not be the final approach selected. Regardless of the process, the reviewer should keep in mind that the purpose of the sensitivity analysis is to evaluate uncertainty and variability in the assessment. One of the simplest methods uses a top-down approach in which the risk reduction of each component (e.g., infiltration, unsaturated zone, wasteform, engineered barriers, saturated zone, biosphere characteristics) of the performance assessment model is identified by starting with a hazard and calculating how each component reduces the risk from the hazard. Subsequently, for the most important components, the licensee performs a quantitative or qualitative evaluation of the parameters to identify those that are most likely to influence the output from the component. Complications arise because an individual component's importance in the system can be relative to the performance of other components. For example, the hydraulic conductivity of a drainage layer may not appear to be risk-significant as long as a cover is assumed to significantly limit water flow, but the drainage layer may be very important to performance if the cover is degraded. Section 7.4.1.2 discusses methods to avoid such problems. Developing an understanding of the importance of parameters and models in a performance assessment is a time-consuming process that is best accomplished by exploring a variety of approaches.

If the licensee has performed a deterministic performance assessment, then the reviewer should examine the sensitivity analyses provided. The reviewer should evaluate the licensee's basis for selecting the parameters and combinations of parameters used in the sensitivity analysis. The ranges in the parameters selected should be consistent with the variability and uncertainty in the parameters, and the selected ranges should provide the reviewer with confidence that the effects of the uncertainty on performance are bounded. The reviewer should examine the technical basis used to support the variability and uncertainty. Appropriate combinations of parameters should be used to capture the interdependence of key parameters and the consequences associated with changes in combinations of key parameters. The reviewer should consider combinations of parameter values that are likely to occur as a result of common causes. For example, an aggressive chemical environment could increase both the corrosion rate of waste containers and the rate of leaching of radionuclides from a wasteform. If a licensee were to perform analysis of the increased corrosion rate independent from analysis of increased leaching rate of radionuclides from the wasteform, the true risk significance of an aggressive chemical environment may not be identified.

Different approaches to performance assessment calculations (e.g., deterministic, probabilistic) have advantages and disadvantages with regard to uncertainty and sensitivity analysis. The type of analyses that may be suitable for a particular problem will be tied the amount of model support available. While deterministic analysis can be a suitable approach for performance assessment, it can also present a challenge for a dynamic system that responds nonlinearly to the independent variables. When there are numerous inputs (e.g., data or models) that are uncertain, evaluating the impacts of the uncertainties on the decision can be difficult. Typical one-off type of sensitivity analysis where a single parameter is increased or decreased will identify only local sensitivity within the parameter space such that it may not clearly identify the risk implications. When a licensee must address multiple uncertainties, isolation of the impact of the uncertainty with one-off sensitivity analyses should be avoided because it can lead to misleading results (see Section 7.4.1.2). In addition, uncertainties should not be relegated to representation in one-off evaluations; uncertainties that are expected to apply to the system should be represented in the compliance case results. A deterministic approach can be useful to bound uncertainty when the analysis can be demonstrated to be conservative. A probabilistic approach can have distinct advantages when there are a number of uncertainties that may significantly influence the results of a performance assessment. For example, the uncertainty introduced by the changing effectiveness of a chemical barrier over time may be represented by selecting appropriate ranges for the radionuclide transport parameters for the materials of the barrier.

3.0 PERFORMANCE ASSESSMENT

A performance assessment is a type of risk analysis that addresses (1) what can happen, (2) how likely it is to happen, and (3) what are the resulting impacts (Eisenberg et al, 1999). These impacts can then be compared to the performance objective in 10 CFR 61.41 (radiological protection of the general public). The requirements for a performance assessment are set forth in 10 CFR 61.13(a), as discussed in Section 1.1.2.1.

This section describes acceptable approaches for conducting a performance assessment to demonstrate that the performance objectives specified at 10 CFR 61.41(a) and (b) would be met. This guidance supplements, rather than replaces, other NRC guidance on acceptable approaches for complying with the requirements specified in 10 CFR Part 61 (see Section 1.2.1). Specifically, this guidance supplements the approach discussed in NUREG-1573 (NRC, 2000a). The approaches described in NUREG-1854, for performance assessment in incidental waste determinations, may also be applicable to the development of a performance assessment for a land disposal facility for low-level waste (NRC, 2007a).

3.1 Performance Assessment Approach

The essential elements of a performance assessment for an LLW disposal site are:

(1) A description of the site and engineered system,

(2) An understanding of FEPs that might affect the disposal system,

(3) A description of processes controlling the movement of radionuclides from the LLW disposal units to the environment,

(4) A computation of doses to members of the public, and

(9) An evaluation of uncertainties.

The methods of performance assessment are matched to the complexity of the problem. Deterministic, bounding analyses can be used for simple evaluations; however, probabilistic analyses may be more appropriate for evaluating the disposal of long-lived waste at LLW disposal sites, to take into account uncertainties over long timeframes.

Many FEPs can influence the ability of a waste disposal facility to limit releases of radioactivity to the environment. While considering the associated uncertainties, a licensee should complete a performance assessment that identifies the FEPs that might affect the disposal system, examines the effects of these FEPs on the performance of the disposal system, and estimates the annual dose to any member of the public caused by relevant FEPs. Section 2.5 provides guidance on the FEPs identification and screening process, including the development of scenarios.

Disposal system behavior is characterized by the disposal facility design, the characteristics of the waste, geologic and environmental characteristics of the disposal site, and processes and events that influence the aforementioned features. The performance assessment identifies the specific characteristics of the disposal site (e.g., hydrology, meteorology, geochemistry, biology, geomorphology); degradation, deterioration, or alteration processes of the engineered barriers (including the wasteform and container); and interactions between the site characteristics and engineered barriers that might affect the performance of the disposal facility. The performance assessment examines the effects of these processes and interactions on the ability of the disposal facility to limit waste releases to the environment that could cause annual dose to a member of the public.

The performance assessment should be performed iteratively and is meant to be a tool for both the licensee and the regulator to use in assessing whether the disposal facility meets the 10 CFR Part 61.41 performance objective. During the design and licensing of a disposal site, assumptions may be made, based on expected waste volumes and streams, of the possible final inventory of a site or a specific disposal unit within a site. As operations occur, these assumptions should be updated periodically with actual waste volumes and any revised information on future waste to be received (see Section 10.0). The results of the performance assessment can then be used to evaluate whether reasonable assurance still remains that the disposal unit or site will continue to meet the performance objectives. If the performance assessment shows that meeting the performance objective is uncertain or unlikely, then the licensee should consider taking the following actions: additional data collection and modeling could be performed, the facility could be modified, or future waste volumes or specific radionuclide quantities or concentrations could be reduced (i.e., through setting “allowable” limits, see Section 9.0). The decisions on what actions to take should involve the site operator, the appropriate regulator(s), and other stakeholders.

3.1.1 Example of a Performance Assessment Approach

An example of an acceptable approach for conducting a performance assessment and demonstrating that the requirements in 10 CFR 61.41 would be met is outlined below. The approach is divided into 12 steps, as shown on Figure 3-1:

- Step 1: Conduct initial data evaluation of information needed to describe the LLW disposal system environment — Formulate the context of the assessment. Describe the disposal system and the environment of the site.
- Step 2: Describe plausible evolutions of the disposal site — Identify and consider credible factors or processes that could contribute to affecting a radionuclide release, including changes to the disposal site over time from natural processes and events, and construct reasonably foreseeable scenarios to evaluate in Step 5 for compliance with the performance objective and less likely, but plausible scenarios for evaluating defense-in-depth in Step 7.
- Step 3: Describe initial conceptual models and parameter values or distributions — Develop site-specific conceptual models based on important disposal site features and processes.
- Step 4: Formulate mathematical models and select codes — Formulate mathematical representations of the conceptual models, using appropriate documentation and quality assurance/quality control (QA/QC). Numerical model development incorporates the mathematical representations and produces computational models with which to run simulations.

- Step 5: Conduct consequence modeling — Estimate performance (e.g., potential dose to members of the public). See Sections 3.4 and 4.3.1 for further discussion. Much of the receptor scenario approach used in Section 4.3.1 can be applied in the performance assessment.
- Step 6: Perform sensitivity and uncertainty analysis — Evaluate which models, assumptions, and combinations of parameters were most significant in producing the resulting doses. Evaluate the scenario, model, and parameter uncertainties.
- Step 7: Demonstrate defense-in-depth — Evaluate whether defense-in-depth protections include multiple, independent and redundant layers of defense using the results of the performance assessment (e.g., uncertainty analysis). See Section 8.0 for further discussion.
- Step 8: Evaluate disposal site adequacy — Compare the results to the performance objective in 10 CFR 61.41 (radiological protection of the general public). If the performance objective has not been met, proceed to Step 8.
- Step 9: Reevaluate data and assumptions — Determine what information and/or data are needed to reduce uncertainty and demonstrate regulations are met.
- Step 10: Collect New Information and/or Change Design — Gather needed information such as site characterization data and modeling studies, or change the facility design.
- Step 11: Update assumptions — Recalculate site performance using updated data and assumptions. Steps 9 through 11 can be performed for as many iterations as needed to demonstrate regulations are met.
- Step 12: Final determination — Make final determination that regulations are met. If the licensee cannot demonstrate that 10 CFR 61.41 would be met at the selected site, they may choose to reject the site as a potential disposal option or place limitations on the inventory that can be accepted for disposal.

Additional guidance on an example performance assessment approach can be found in NUREG-1573, Section 3.1 (NRC, 2000a). Sections 2.0 of this document provide additional guidance on Steps 1 through 4 above.

3.1.2 Role of the Performance Assessment

To obtain a license to receive, possess, and dispose of LLW, disposal facility operators should use the performance assessment to demonstrate, with reasonable assurance, that the 10 CFR 61.41 performance objective for protection of the general public will be met. Further, the results of a performance assessment can be used to support defense-in-depth analyses required in 10 CFR 61.13(f). Licensees may use the results of the performance assessment to quantify barrier capabilities and their associated uncertainties to understand their contribution to safety and defense-in-depth. Section 8.0 of this document provides additional guidance on using the results of the performance assessment to demonstrate defense-in-depth protections are included.

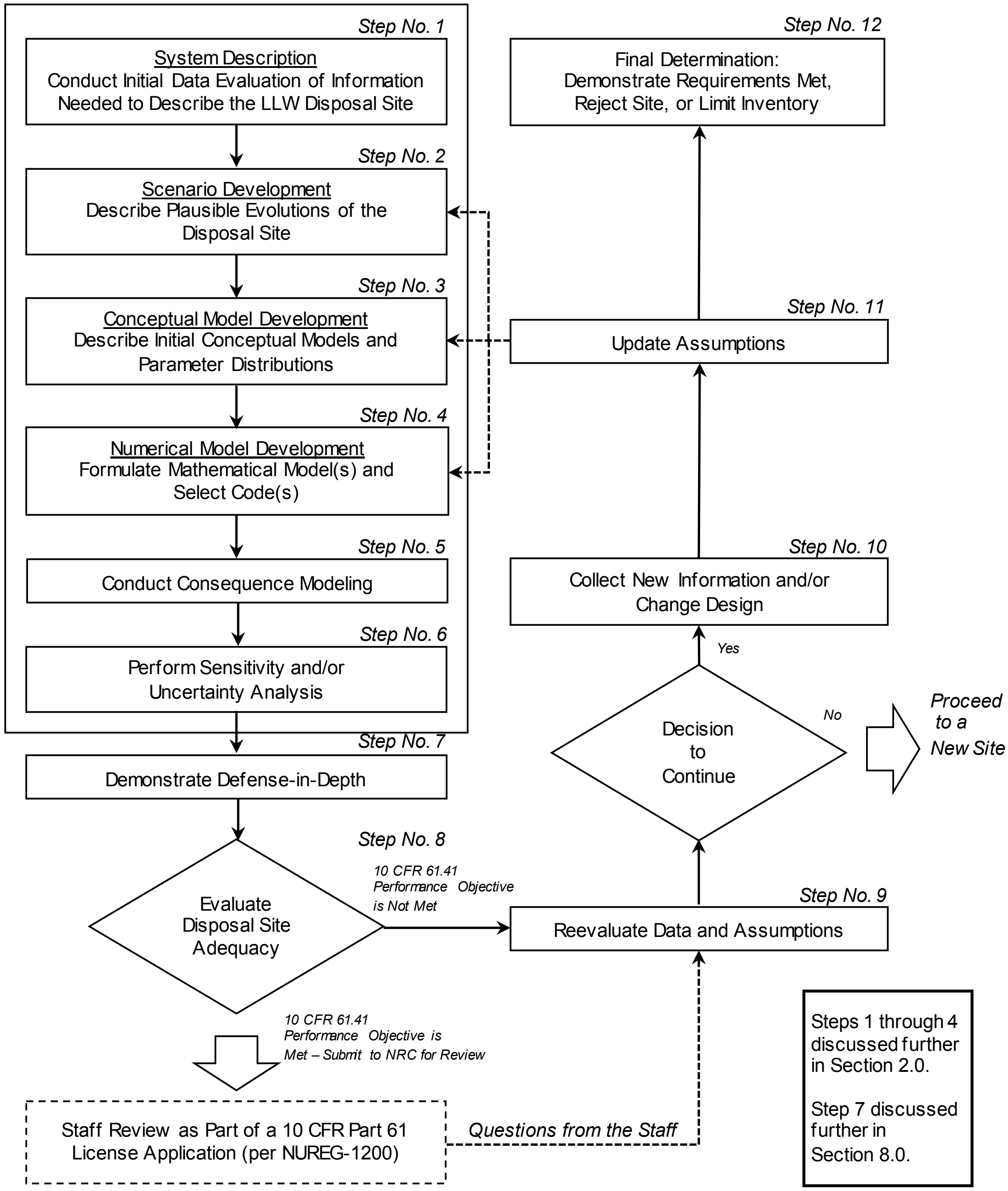


Figure 3-1 Example of a Performance Assessment Process

During construction, operation, and post-closure periods of the LLW disposal facility, the performance assessment can continue to have an important role in demonstrating that the performance objectives continue to be met. The performance assessment is a projection into the future to provide the bases for the decision to proceed.

The other steps in the operation and closure process can be used to confirm (or refute) the basis for the initial decision. For example, 10 CFR 61.53 requires a licensee to perform environmental monitoring during the construction, operation, and post-operational periods. Similarly, 10 CFR 61.28 requires that a final revision to site closure plans should contain any additional geologic, hydrologic, or other disposal data obtained during the operational period pertinent to the long-term containment of waste, and the results of tests, experiments, or analyses pertaining to the long-term containment of waste, including revised analyses for 10 CFR 61.13 using the details of the final closure plan and waste inventory. Site closure may be authorized only if the final site closure plan provides reasonable assurance of the long-term safety of the facility.

The performance assessment can be used to address these requirements by updating the performance assessment model developed for the initial license application with the new information from these monitoring programs. These new site data might validate or refute the key parameters or model assumptions used in the initial performance assessment. Section 9.5 provides information on mitigation, which might be identified as being necessary to continue meeting the 10 CFR Part 61 performance objectives as a result of conducting an updated performance assessment upon site closure. Section 10.0 of this document discusses the role of performance assessment in performance confirmation. Additional discussion of general technical elements as they relate to performance assessment appears in Sections 2.0 of this document.

The following sections are a continuation of the discussion presented in Section 3.3 of NUREG-1573 (NRC, 2000a), but with an emphasis on analyses for waste containing long-lived radionuclides. Licensees can use the guidance contained in this section to support demonstration that the the 10 CFR 61.41(a) and (b) performance objectives are met and in some cases to support demonstration that the 10 CFR 61.41(c) performance objective is met. Section 3.2 discusses radionuclide source term modeling and release of radionuclides from the disposal units. Section 3.3 discusses radionuclide transport through the environment of the disposal site. Section 3.4 discusses modeling of the biosphere.

3.2 Source Term

The objective of source term modeling is to calculate radionuclide releases from the disposal units over time and space. Licensees can use the calculated release rates as input for transport models (see Section 3.3) that estimate offsite releases for the facility. The source term includes the inventory, physical and chemical characteristics, and other properties of the waste used to estimate release rates. The inventory of waste is the physical amount of material and quantity of radioactivity contained in the waste. Releases generally occur by advective or diffusive mechanisms, although direct release mechanisms may be possible (e.g., biointrusion, erosion). Release rates are also a function of the conditions of the environment immediately surrounding the waste (i.e., the near-field environment). The near-field environment may have hydrological and chemical conditions that differ significantly from the natural system in which the waste disposal facility is located. Additional releases to the aqueous phase and, for certain radionuclides (e.g., carbon-14, hydrogen-3, radon-222), to the gaseous phase, can also occur. Licensees may simulate many intermediate processes to estimate release rates. Release rates can be affected by the performance of engineered barriers (e.g., waste containers) and the wasteforms, the chemical properties of the disposal system, and the interaction of the disposal system with the natural environment in which it is located. Licensees should identify these processes using the guidance in Section 2.5 regarding the analysis of FEPs. Some disposal facilities will require detailed consideration of these processes and conditions, whereas simplified analyses may be justified for other sites and disposal facilities. Licensees should carefully consider the source term models for those disposal sites where significant credit is taken for some aspect of the source-term modeling (e.g., low *solubility limits*), attributes are relied upon for defense-in-depth protections, or higher long-term hazard exists, and for which there is limited model support. Facilities for which a simpler, less complex, analysis may be acceptable include those where a licensee can show that a simple analysis is clearly conservative or where a licensee provides a simple model that is well-supported by multiple lines of evidence, including field tests demonstrating that the model estimates are accurately representative or bounded by field data.

A reviewer may want to use the following simple factors when risk-informing their review effort: hazard, credit, and support. For example, a disposal site may have a hazard that is large and persistent, the licensee may have taken significant credit in their technical analyses for release rate modeling, and they have limited information available to support their release rate modeling. In this case, the reviewer should apply additional resources to their review effort compared to an instance where a disposal site presents a small hazard and the licensee develops well-supported technical analyses.

This section of the guidance focuses on the assumptions, data, and models (conceptual and mathematical) that a licensee may use to develop the source term abstraction for the performance assessment. Most disposal sites and proposed disposal practices vary significantly, therefore, source term abstractions are usually developed on a site-specific basis. A licensee should develop the source term abstraction to:

- include the effects of degradation processes on the performance of the wasteform and the engineered barriers
- consider the physiochemical processes associated with partitioning of radionuclides between the waste and the physical phases in the disposal unit, as appropriate
- include temporal and spatial variation in the inventory, degradation processes, and physicochemical processes that are significant to performance
- adequately represent the features and processes significant to disposal system performance
- simulate the behavior of the system to the extent that disposal system performance is adequately represented

The source term model should be integrated with other models, such as climate, infiltration, and radionuclide transport, over both space and time. Guidance on modeling climate and infiltration appears in Section 3.3.3 of NUREG-1573 (NRC, 2000a) and Section 4.3.1 of NUREG-1854

(NRC, 2007a). Section 3.3.7 of NUREG-1573 and Section 4.3.5 of NUREG-1854 present guidance on radionuclide transport, biosphere characteristics, and dose modeling.

Section 2.7.2 of this guidance document describes general elements of technical analyses that are applicable to the review of a source term abstraction for performance assessment. Since this guidance supplements existing guidance, licensees and reviewers may also consult NUREG-1573, Section 3.3.5, for further guidance on source term modeling. Also, NUREG-1854, Section 4.3.3, may assist reviewers in considerations for acceptable source term modeling that may apply to review of a performance assessment for a LLW disposal facility.

The following sections of this document provide specific guidance on aspects of source term modeling. Section 3.2.1 describes approaches for developing the inventory representation. Section 3.2.2 discusses guidance related to representing the chemical environment in the performance assessment. Sections 3.2.3 and 3.2.4 discuss guidance on representing the waste containers and wasteforms, respectively, and the effect of degradation processes on their longevity. Sections 3.2.5, 3.2.6, and 3.2.7 describe approaches for modeling aqueous, gaseous, and direct releases.

3.2.1 Inventory

The inventory representation provides the *radionuclide inventory* for which release rates are estimated with source term calculations. Sections 3.3.5.1, 3.3.5.2, and 3.3.5.7 of NUREG-1573 (NRC, 2000a) and Sections 3.1 and 4.3.3.1.1 of NUREG-1854 (NRC, 2007a), as applicable to LLW disposal facilities, provide guidance on recommended approaches for developing and reviewing waste inventory to support performance assessment modeling.

The radiological inventory to be disposed of is a key input parameter to the performance assessment. In addition, the physical and chemical characteristics of the waste can determine release rates. Physical characteristics can affect the stability of the waste and the stability of the disposal facility (see Section 5.0). Chemical characteristics can affect the retention of radionuclides within the disposal facility. Chelating or complexing agents can significantly increase the mobility and effective solubility of the radionuclides in the disposal environment.

A licensee should develop an inventory description that provides the total activity (by radionuclide), concentrations, and physical and chemical forms of the waste to be disposed of, including spatial configurations. The inventory description should include the radiological inventory at the time of disposal, as well as the projection of inventory over the time period of interest to account for decay and ingrowth.

Although Tables 1 and 2 of 10 CFR 61.55 list isotopes for the purposes of waste classification, the inventory that a licensee evaluates in the performance assessment may be more extensive. The performance assessment inventory should not be limited to the radionuclides in Tables 1 and 2 unless adequately justified. For example, chlorine-36 and neptunium-237 are not listed in Tables 1 and 2 but are present in some LLW streams and are long-lived and mobile in the environment. Licensees should provide estimates of radionuclides that are not listed in these tables, as well as a basis for their derivation. Licensees may use indirect methods of estimating the inventory of some radionuclides when direct methods are not available, are not technically feasible, or are cost prohibitive. Indirect methods of estimating inventory have additional uncertainty that should be reflected in inventory estimates. When using indirect methods to estimate the inventory, the licensee should describe where the waste has been generated and what isotopes are used or created in the associated processes.

Different waste streams may have significantly different characteristics. However, it may be useful for a licensee to compare their projected inventory to the inventory of other LLW disposal facilities. The similarity or dissimilarity of the radiological inventories can help a reviewer to identify isotopes that may dictate the need for a more detailed review of the inventory estimates. In some cases, specific isotopes may be reported as less than a particular value because the isotope was below the lower detection limit of the characterization technique. It is acceptable to assign inventory based on the lower detection limit for initial screening. However, if the initial screening identifies that specific isotope inventory as significant, then additional characterization (either direct or indirect) may be necessary to determine the actual inventory with greater confidence. It is generally not acceptable to assume a value of zero for the inventory of radionuclides that are less than the lower detection limit unless there is adequate justification that the radionuclide is not present in the waste.

3.2.2 Chemical Environment

Estimation of the chemistry of the environment within the disposal units may be needed for use in source term models. The chemical environment may have impacts on and be affected by the lifetime of engineered barriers and waste containers, releases of radionuclides from the wasteforms, and mobility within the disposal units. The chemical environment in the disposal site is likely to be dynamic unless the site has been engineered to provide a more stable chemical environment. The chemistry of the disposal units would likely have an impact on solubility limits or retardation of radionuclides that are common parameters in modeling release rates from the source term and through the environment. Geochemical considerations may include solid composition, pH, buffering capacity, reduction-oxidation potential, partitioning processes, and the presence of colloidal particles and ligands.

In general, licensees are encouraged to collect site-specific information to justify parameters that would be expected to significantly enhance or retard the release and migration of radionuclides or that are relied upon for defense-in-depth protections. Licensees may use sensitivity analyses to identify the importance of geochemical parameters on the resulting dose either to identify whether site-specific data should be obtained for significant parameters, or to determine whether the range of values used is sufficiently conservative for parameters that do not have a significant effect. Section 2.2.2 presents guidance on the treatment of uncertainty. It may also be appropriate to use other means to justify parameters, such as values from available literature, appropriate geochemical process modeling (e.g., MINTEQA2 (EPA, 1991); EQ3/6 (Daveler and Wolery, 1992; Wolery, 1992a and 1992b; Wolery and Daveler, 1992); PHREEQC (USGS, 1999); Geochemists Workbench® (Bethke and Yeakel, 2009a–d)),[1] or expert judgment and expert elicitation (see Section 2.2.3.1). Licensees should judiciously select the proper literature values for significant parameters and transparently describe the similarities and discrepancies between the site conditions to which they are proposed to represent and the conditions from which the literature values were derived. A reviewer should determine if the

[1] NRC does not endorse or recommend any specific code or model for geochemical modeling. Licensees are free to select and justify their particular code or model for their application. Regardless of the code selected, it is important that the code meet all applicable quality assurance requirements.

literature values were developed under appropriately representative conditions. If the conditions under which the literature values were derived are not known, then the data should not be used.

The abstraction for the chemical environment should consider the uncertainty and variability in developing geochemical parameters. Variability in the chemical environment of a site can occur spatially and temporally. Spatial variability may arise from heterogeneities in wasteforms and other materials introduced to the disposal units (e.g., backfill materials, cementitious materials). Temporal variability may arise from the degradation of engineered barriers, waste containers, and wasteforms as well as the evolution of the disposal site environment to future conditions. Licensees should consider the impacts of the evolution of the natural environment on the chemical environment as a result of degradation of the engineered barriers and natural processes such as climate change. A licensee should document their treatment of spatial and temporal variability in the chemical environment model. The documentation should provide the technical basis for the representation. For example, if a constant environment was used in the performance assessment modeling, the licensee should demonstrate why the constant environment was representative or conservative with respect to the projected future chemical environment.

Section 3.3.5.6 of NUREG-1573 presents guidance on considerations and issues associated with developing models for the chemical environment of the disposal units (NRC, 2000a). Section 4.3.3.1.4 of NUREG-1854 provides guidance on reviewing a chemical environment representation (NRC, 2007a). Additional considerations, as they apply to a specific facility, may also be found in Section 4.2.1.3.3 of NUREG-1804, Revision 2, "Yucca Mountain Review Plan," issued July 2003 (NRC, 2003c).

3.2.3 Waste Container

Waste container modeling describes the waste containers and estimates their longevity for use in source term models. In the past, licensees have generally not taken much credit for the performance of waste containers in their technical analyses; however, they are not prohibited from doing so. The waste container modeling should consider degradation processes (e.g., corrosion, mechanical degradation) for the various waste containers and should be consistent with the evolution of the chemical environment (see Section 3.2.2). The performance of the waste containers may also affect the degradation of wasteforms and is important for estimating radionuclide release in the source term models. Section 3.3.5.4 of NUREG-1573 includes guidance on evaluating the performance of waste containers (NRC, 2000a). In addition, waste containers are a component of an engineered barrier system. Therefore, reviewers may want to consult applicable guidance on reviewing engineered barriers in Section 3.3.4 of NUREG-1573 and Section 4.3.2 of NUREG-1854 (NRC, 2007a). Sections 4.2.1.3.1 and 4.2.1.3.2 of NUREG-1804 present additional considerations for the performance of engineered barriers with respect to the waste containers (NRC, 2003c).

Metallic containers will undergo corrosion over time. Most metallic containers used in LLW disposal are carbon steel; however, other types of steel may be more commonly used in the future. If a licensee takes credit for waste containers in the performance assessment, they should provide a degradation analysis to justify the performance of the containers. The degradation analysis should look at the degradation processes (e.g., general corrosion, stress-corrosion cracking, localized corrosion, galvanic corrosion, radiolytic effects) and the disposal environment to estimate future performance. The degradation analysis should consider the initial condition of the containers (e.g., corrosion prior to disposal). In humid disposal environments, failure of carbon steel containers due to general corrosion is expected to be relatively quick, such that little credit for performance (e.g., delay in releases) is commonly taken in the analyses. In arid environments, licensees may take more credit for container performance, if supported by the degradation analysis which will examine the materials, environmental conditions, and degradation mechanisms. Licensees should support engineering analysis of container performance with measurements in relevant environmental conditions. In addition, licensees should provide real-world engineering analogs. The engineering analogs should be for similar exposure conditions and should not include maintenance, since the disposal containers will not be maintained after disposal. Section 2.2.3 provides additional information with respect to developing model support, including the use of analogs.

Analysis of container failure will need to consider variability, as leakage from containers may occur as soon as the first perforation occurs. The state of corrosion that defines "failure" will be different for different release mechanisms. A perforated waste container may still provide a significant barrier to mass transfer processes for some time. However, in general, when the corroded area exceeds approximately 10 percent, the container can be considered to be failed from an advective release standpoint due to shedding of water from intact areas to failed areas.

Containers made of other (i.e., non-metallic) materials will experience degradation unique to the material type. Reviewers should evaluate proposed container lifetimes for different materials on a case-by-case basis. In general, the licensee's associated degradation analysis will need to provide the following:

- an assessment of the relevant degradation mechanisms
- a description of the environmental conditions including variability and uncertainty
- analysis of the expected performance
- an assessment of potential unexpected performance and the likelihood of the unexpected performance
- data from laboratory, field, and/or analog observations that support the expected performance

3.2.4 Wasteform and Waste Type

The wasteform modeling representation is used to describe wasteform performance, including variability. Wasteform performance is used in source term models. The modeling should consider degradation processes for the various wasteforms to estimate their performance consistent with the evolution of the chemical environment in the disposal units over the time period of interest (see Section 3.2.2). The performance of the wasteform is important for estimating radionuclide release in the source term models.

The branch technical position on wasteform provides recommendations and guidance on acceptable methods to demonstrate that waste stability requirements have been met (NRC, 1991b). Appendix A to the technical position on wasteform provides methods to ensure the suitability of cement-stabilized wasteforms. *Geochemical Aspects of Radioactive Waste Disposal* describes some wasteforms and their properties (Brookins, 1984). Every wasteform is different and can have different characteristics. However, the main elements in Appendix A of the wasteform BTP apply to wasteforms other than cement-based wasteforms.

These elements include:

- qualification testing,
- quality of sample preparation,
- consideration of variability,
- waste characterization, and
- short- and long-term specimens including *surveillance* specimens.

It is important for licensees and reviewers to note that waste stability from a structural standpoint does not necessarily translate into acceptable performance for waste leaching. Depending on the concentration of radioisotopes in the waste, the fractional release rate of an individual isotope necessary to demonstrate that the performance objectives would be met may be lower than that necessary to demonstrate waste stability.

Radionuclide release from wasteforms can be very complex, with a number of processes controlling the mobility and concentrations of radionuclides. Processes such as complexation reactions, acid-base reactions, oxidation-reduction reactions, dissolution and precipitation reactions, sorption and ion-exchange reactions, biodegradation of organic matter, and radioactive decay and ingrowth can impact waste release rates. A variety of test methods and modeling approaches have been developed to characterize the release of contaminants (NRC, 2010). The following guidance is developed on the basis of information in NUREG/CR-7025. In this report, Ebert identified a number of key lessons with respect to waste release that included:

- Test results can be misinterpreted if testing artifacts are not taken into account (e.g., interval for solution replacement, flow rates, failure to reach steady state, modeling of inappropriate processes).
- A single test method may not identify mechanisms controlling release.
- It is necessary to identify which processes control release under the conditions of interest (i.e., the test conditions should be representative of expected conditions, including variability).
- Laboratory test results need to be translated to long-term material behavior (i.e., appropriate scaling, which may include multiple variables, is necessary).

The objective of laboratory testing is for a licensee to identify the process (or processes) that will control the release of radionuclides over long periods of time, collect data to parameterize models that quantify release, and then integrate the waste release model into a performance assessment.

Test methods can be categorized as static, semi-static (where part or all of the solution is exchanged during the test), or dynamic (where solution flows continuously). Different test methods can yield different results; licensees should carefully interpret the test results to avoid misinterpretation or mischaracterization of the release mechanism. For example, the American Nuclear Society 16.1 (ANS, 2008) leaching method is a solution-exchange test to characterize diffusion-controlled release. The test results are sensitive to the sampling intervals that are used to measure the extent of component releases. While the test is useful for screening, it is not recommended for modeling long-term waste degradation. Methods such as American Society for Testing and Materials (ASTM) C1308-08 (ASTM, 2009), which uses constant exchange intervals, may be more useful in determining whether waste release is diffusion controlled or affinity controlled. Column tests are useful in simulating the infiltration of water through the subsurface to waste and the dissolution of contacted materials. The measured dissolution rate in column tests is a function of the flow rate of the solution and the reactive surface area that is contacted. Different column tests may need to be performed for different materials and to account for the variable emplacement of those materials. A primary challenge is the scaling of the laboratory results to the field which may have much different flow rates and reactive surface areas than used in the laboratory. Additionally, the flow rates and reactive surface areas in the wasteform can vary over time. When some materials leach, the reactive surface area may increase or decrease from the leaching process. Release rates from some materials may be much higher under conditions of wet-dry cycling as compared to non-dynamic conditions. The value of column tests (or tests such as field-scale lysimeters) is to confirm that the appropriate performance models are used to quantify the processes that control radionuclide release, especially when calibrated to the system of interest.

Because of the complexity of waste release modeling, the NRC staff recommends that licensees complete a blind validation of the numerical model results to test the predictive capabilities of the numerical model. This is done by establishing a condition for which waste release measurements have not been completed and performing numerical simulations of the waste release that would be expected to occur under those conditions. This is followed by experimental or field measurements of the actual waste release that is compared to the numerical modeling. Licensees should establish criteria before the blind comparison to define acceptable agreement between the numerical modeling results and the experimental measurements.

Additional information can be found Section 3.3.5.4 of NUREG-1573, which includes guidance on information to characterize wasteforms and types (NRC, 2000a). Section 4.3.3.1.2 of NUREG-1854 presents guidance on wasteforms and their time-dependent degradation (NRC, 2007a).

3.2.5 Aqueous Release

The models for aqueous releases estimate the rate of radionuclides released from the disposal units in water contacting the wasteforms. The four general types of aqueous radionuclide releases are: (1) rinse release, (2) diffusional release, (3) dissolutional release, and (4) partitioning release. Rinse release refers to washing of radionuclides from the surface of a wasteform by infiltrating groundwater. Diffusional releases occur when radionuclide movement through a porous wasteform (e.g., a cement-stabilized wasteform) is limited by diffusion. Diffusion can occur in any media in the presence of a concentration gradient. Radionuclide releases resulting from corrosion of an activated metal or dissolution of glass wasteforms are examples of dissolutional release. Partitioning release results when radionuclide release is described by a characteristic partitioning parameter (e.g., sorption coefficient) that distributes the activity between phases in the system (e.g., between the solid wasteform and liquid water phases).

An aqueous release model will be a function of the wasteforms, radionuclides, geochemical environment, and amount of water contacting the wasteforms. Licensees should integrate the aqueous release model with these related models. Methods to represent aqueous release have been incorporated into numerical models such as Disposal Unit Source Term — Multiple Species — Distributed Failure (DUSTMS-D) (Sullivan, 2006) and Breach, Leach, Transport, and Equilibrium Chemistry (BLT-EC) (NRC, 1995e). Though it is difficult to provide model support for the overall performance assessment model, licensees can provide support for individual process models or abstractions (as discussed in Section 2.2.3). For example, licensees should provide support for numerical modeling results of aqueous release.

Licensees should consider comparison of laboratory test results, such as leaching experiments, with numerical modeling results. If field data are available, they provide information that can be used for model support. For example, observed concentrations of radionuclides in leachate collection systems can be compared to modeled release rates. Section 4.3.3.2 of NUREG-1854 (NRC, 2007a) and Section 4.3.1.2.4 of NUREG-1804 (NRC, 2003c) provide additional guidance on potential considerations for development or review of aqueous release models.

3.2.6 Gaseous Release

Models for gaseous release estimate the rate of radionuclides released in the gas phase from the disposal units to the atmosphere above the disposal facility. A gaseous release model may also need to consider the generation of nonradioactive gases and their impact on the capabilities of the disposal facility to contain and isolate the radioactive waste. Examples of important radionuclides that should be considered and evaluated by licensees for gaseous release include C-14, Kr-85, Rn-222, H-3, and I-129. Gaseous releases are dependent on both generation of the gas and transport through fluids within the disposal units to the atmosphere. Discrete features such as fractures or a gap between materials can have a significant impact on gaseous release rates.

In Section 3.3.5.7.2 of NUREG-1573, the NRC staff recommends a screening approach to determine if gaseous releases from the disposal facility might contribute significantly to dose (NRC, 2000a). Licensees may apply this approach to determine whether more realistic release rates would be needed. More realistic release rates may be developed by licensees using approaches described in NUREG-1573 or approaches listed in the discussions below. Realistic release rate modeling should consider the specific processes affecting generation and transport of gaseous radionuclides or empirical models of gaseous release rates. In general, licensees are encouraged to collect site-specific information to justify parameters that would be expected to significantly enhance or retard the release and migration of gaseous radionuclides should they significantly affect doses to a member of the public.

3.2.6.1 *Gas Generation*

Gases generated in a LLW disposal facility may result directly from disposal of certain waste streams (e.g., Kr-85) or from various processes external or internal to the disposal site. Processes generating gases, many of which are discussed in Section 3.3.5.7.1 of NUREG-1573, may include: (1) corrosion of metals in waste and its packaging, (2) microbial degradation of organic waste components, (3) radiolysis of waste, its packaging, or the surrounding backfill material, (4) volatilization of certain wastes (e.g., iodine-129), and (5) decay of radionuclides with primordial origin (e.g., uranium-238 or thorium-232) to gaseous progeny (e.g., radon-222). Rodwell et al. (2003) summarizes considerations for many of these processes as they relate to deep geological radioactive waste repositories. This information may be relevant for licensees to consider in a performance assessment for LLW disposal facilities. The evaluation of gas generation by a licensee should account for the nature of the waste, the radionuclides it contains, the waste packaging materials, and the chemical characteristics of the environment within the disposal units (e.g., saturation, groundwater composition, pH, Eh, and backfill materials) (NEA/OECD, 2001).

3.2.6.2 *Radon Emanation*

Conservation of linear momentum in the alpha-decay process of high-specific-activity radionuclides can result in transport of radionuclides (i.e., alpha recoil). Typically this process is not significant for the release and transport of radionuclides from a LLW disposal facility. However, alpha recoil can be significant for certain gaseous radionuclides (e.g., radon) associated with some long-lived waste streams. Alpha recoil can result in newly created radon atoms moving away from their original location. Some end up in the particles (media) where they were created, some end up in adjacent particles, and some end up in the pore space. The radon emanation coefficient is a dimensionless parameter that expresses the fraction of radon released to the pores (compared to the total volume). Guidance on the radon emanation coefficient is provided here due to the potential significance of this unique process and radon's presence in the decay chain for long-lived waste streams associated with uranium.

The radon emanation coefficient is strongly influenced by the liquid saturation of the medium (Nazaroff et al., 1988). As liquid saturations vary temporally and spatially, it is expected that radon emanation coefficients will also exhibit temporal and spatial variability. The values for radon emanation coefficients depend on the liquid saturation (or moisture content), the media, and the radon isotope.

Yu et al. (1993) provides a limited compilation of radon emanation coefficients. The compilation shows the large variability that can be observed; soil values ranged from 0.02 to 0.70. Nielsen and Rogers (1988) provides a probability plot of emanation coefficients for 56 soils. The values range from approximately 0.08 to 0.44 (with a mean of 0.22), consistent with the observed variability in the data of Yu et al. Regulatory Guide 3.64, "Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers" (NRC, 1989a) for calculation of radon fluxes from mill tailings covers recommends a default value of 0.35 for design, which would correspond to a 98th percentile value from the Nielson and Rogers data *for soil.* The challenge is that the data represent both intra- and inter-site variability. If site-specific measurements are not available, licensees should select conservative values from the compilations (as was done in Regulatory Guide 3.64) because the inter-site variability should not be credited in a site-specific analysis. For long-term performance assessment calculations, it is important to recognize that the values selected for the analysis are representative of values anticipated for the evolution of site conditions. Average parameter values (spatial and temporal) can be used if it can be demonstrated that the variability is not important to estimating radon fluxes. However, because of the nonlinear processes governing radon release and transport, the variability in emanation coefficients and other parameters may drive the long-term fluxes. For example, at a moderately humid site, radon fluxes may be dominated by the periodic dry conditions.

3.2.6.3 *Gas Transport*

Once gases are released from the wasteforms and containers, they may migrate from the location where they are generated to the atmosphere above the disposal facility. If gaseous release is a significant release pathway, licensees may need to perform gas transport modeling. Mechanisms of soil gas transport in unsaturated systems, as are commonly encountered in the near surface, and mathematical models to simulate these mechanisms are summarized in more detail by Scanlon et al. (2000). Similar to aqueous migration in the environment, the transport of gas can also be described by advection and dispersion.

Advection of gaseous radionuclides from a disposal unit may result from pressure gradients (e.g., barometric pumping) leading to gas flows from areas of higher pressure to areas of lower pressure. Pressure gradients, particularly those driven by atmospheric conditions, can be variable, and releases may be dominated by episodic changes. Licensees should assess the impact of this variability, if significant, on releases of gaseous radionuclides. Advection is affected by the pressure gradient, gas characteristics (e.g., viscosity), and properties of the solid media (e.g., permeability) and generally dominates transport under a pressure gradient when the mean free path of gas molecules is much less than the pore radius and the particle radius of the solid media through which the gas is moving (Cunningham and Williams, 1980). Darcy's Law is typically used to mathematically model advective transport in gases. Depending on the dimensions of the pore space and pressure, a coupling of advective flow to diffusion occurs in gas transport as a result of the increasing importance of molecules-to-wall interactions (Bodvarsson et al., 2000).

Diffusive processes may include Fickian molecular diffusion as well as non-Fickian processes such as Knudsen and non-equimolar diffusion depending on the pressure gradients, dimensions of the pore space, and mean free paths of the molecular motion. Several mathematical models (e.g., Fick's Law, Stefan-Maxwell equations, Dusty Gas Model) exist for diffusive transport depending on pressure gradient, permeability, and concentration conditions (Scanlon et al., 2000). Because of the challenges in mechanistically modeling diffusion through heterogeneous media, an empirical effective diffusivity of the gas in the geologic material through which the gas migrates is often used to account for the various characteristics. The effective diffusivity is sensitive to the availability of interconnected air space and thus to the total porosity, air-filled porosity, moisture content, tortuosity of pores and fractures, and soil structure. Various relationships have been hypothesized to estimate effective diffusion coefficients in soils (e.g., Buckingham, 1904; Penman, 1940; Millington, 1959; Millington and Quirk, 1960; Troeh et al., 1982; Nielson et al, 1984; Kristensen et al., 2010), but their predictive capabilities may be sensitive to actual site conditions (Moldrup et al., 2004; Allaire et al., 2008). Also, literature values for effective diffusion coefficients often employ varied definitions. For example, Culot et al. (1976) note that various definitions of the effective diffusion coefficient for gas diffusion of radon in concrete are contained in the literature. Regulatory Guide 3.64 (Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers) provides guidance on an acceptable method to assess long-term radon diffusion through earthen cover materials for uranium mill tailings sites and may also be applicable to LLW disposal (NRC, 1989a). Licensees should demonstrate that parameters describing diffusion of gaseous radionuclides are adequately justified and account for actual site conditions including uncertainty and variability and the effect of the evolution of site conditions over time on the parameters.

Licensees that undertake more detailed modeling of gas phase transport from disposal units may need to consider some or all of the aforementioned processes and models in the models for gaseous release, depending on the site conditions. For instance, molecular diffusion may be the only mechanism to consider for equimolar gases under isobaric, isothermal conditions that diffuse in pores much larger than the mean free path of the gas molecules, whereas a Dusty Gas Model approach might be necessary for gas migration through low-permeability materials under a pressure gradient to account for coupled advective-diffusive processes. Important parameters of these models (e.g., permeability, saturation, pore space dimensions) should be well-supported and, to the extent practicable, based on conditions that are representative of the site environment. In other words, site observations supporting parameter values should be made under expected conditions for the site and not biased toward conditions that are rare, extreme, or unlikely at the site, particularly if the unlikely conditions lead to overly optimistic behavior of the disposal system. Uncertainty in the parameters may also be significant. For instance, permeability may span a broad range of values depending on the soil types (Nazaroff, 1992). Therefore, the analysis of uncertainty in significant parameters should consider the range of conditions expected for the disposal site. Partitioning of gaseous radionuclides between phases may also affect transport of radionuclides that are generated in the gas phase. In addition, biological activity and isotopic dilution (i.e., dilution of a radioisotope with stable isotopes of the same element) may also have a significant impact on the transport of certain gaseous radionuclides (e.g., carbon-14) (Bracke and Müller, 2008).

Changes in cover properties that are responsible for increasing the hydraulic conductivity may also affect the migration of radon-222 through the cover. Licensees can design cover materials to inhibit radon migration, so that radon flux at the surface is reduced by radioactive decay during transport to the surface (NRC, 1984). However, preferential flow paths can develop in clay barriers in conventional covers (Albright et al., 2006a; Albright et al., 2006b). Preferential flow paths may lead to advective transport of radon. Typically radon migration is controlled by diffusion which is dependent on the inter-connected porosity and moisture content of the soil or clay radon barrier (NRC, 1989a). In addition to enhanced diffusive transport, advection may also contribute to significant migration of radon via these preferential pathways (NRC, 1984). NUREG/CR-3395, "Influence of Cover Defects on the Attenuation of Radon with Earthen Cover" states that models for radon migration in cracks are typically designed for simple geometries that do not account for all dynamic processes resulting in a possible underestimation of radon flux (NRC, 1983a). The recommendation from NUREG/CR-3395 is to apply cover design and development methods so as to avoid the formation of defects (i.e., avoid cracks) in light of this uncertainty.

3.2.7 Direct Release

Licensees may need to represent the direct release of radionuclides into the environment. Models for direct release estimate the rate of radionuclides released directly to the surface as the result of natural FEPs. Anthropogenic direct releases are considered in the inadvertent intrusion assessment, which is discussed in Section 4.0. Direct releases may be caused by processes such as plant uptake, bioturbation (e.g., burrowing animals), natural disruptive events (e.g., faulting), and geomorphological processes (e.g., erosion). For guidance on consideration of natural disruptive events and geomorphological processes, licensees and reviewers should consult Section 5.0 of this document regarding the demonstration that the performance objective for site stability would be met. Direct release can impact the demonstration that 10 CFR 61.41 and 10 CFR 61.42 would be met. Licensees should integrate direct release calculations with other models as necessary, such as with climate and radionuclide transport. Additionally, direct release calculations should consider the long-term evolution of the site environment and its impact on the evolution of the site's geomorphology and ecology. For instance, future climate states may be wetter, leading to increased erosion rates or changes in vegetation or communities of burrowing animals. Erosion or burrowing animals are processes that can lead to direct releases. Licensees may use analog sites with climates similar to the expected future climate for the disposal facility to justify the progression of ecological communities at the disposal site.

3.2.8 Biota Enhanced Release

"Biota enhanced release" is defined in this section as the direct and indirect processes that facilitate release of radioactivity from a disposal facility. Damage of an engineered cover by burrowing animals is an example of an indirect effect of biota on performance of the LLW disposal facility. Biotic transport, as defined in Section 3.3.4 of this document, is defined as the transport of radionuclides in the environment via biota after radioactivity is released.

Biota enhanced release is not usually considered to be a significant pathway in performance assessments. However, the importance of biotic release and subsequent human exposures depends on a variety of factors, including site location, design of the disposal facility, and the wasteforms disposed of at the site. For example, plant uptake and the impact of burrowing animals is much more likely for shallow disposal than for deeper disposal. Therefore, a reviewer evaluating radionuclide release from a site should include consideration of the impacts associated with biotic enhanced release. Current LLW disposal facilities attempt to minimize the impacts of plants and animals by incorporating design features such as engineered cover systems and the use of concrete and steel in the construction of the vaults and waste containers.

Section 5.9.1, "Background," of National Council on Radiation Protection and Measurements (NCRP) 152, "Performance Assessment of Near-Surface Facilities for Disposal of Low-Level Radioactive Waste," lists numerous references of studies of biotic processes conducted at LLW disposal facilities (NCRP, 2005). The long-term contributions of biotic enhanced release processes, including their impacts on engineered wasteforms and barriers, associated with recent LLW disposal facilities are uncertain. Biotic enhanced release has been observed for a wide variety of contaminant release problems; however, biotic enhanced release is typically not a primary release mechanism.

A study conducted by McKenzie et al. (NRC, 1982d) identifies and discusses the mechanisms of biotic release and transport and human exposure associated with arid and moist sites. Based on this qualitative analysis, the authors of that study concluded that penetration of buried waste and enhanced release by burrowing animals and plant roots were potentially important mechanisms in the case of waste disposed in trenches. These studies demonstrate that there are three general primary effects of biota on an LLW disposal facility: biotic release, biotic transport (Section 3.3.4), and secondary transport. This section focuses on intrusion and indirect effects which can enhance release through other mechanisms. Depending on the characteristics of the disposal facility and its environmental settings, biota could influence the performance of a disposal system and lead to significant pathways of human exposure.

Intrusion and active transport occur when biota penetrate the waste zone causing the redistribution of waste material or contaminated soil and resultant release from the disposal facility. Including land management, such as limiting vegetation and minimizing the intrusion by animals, within the scope of management of LLW disposal facilities can reduce the impact of biointrusion during the period of institutional control. Licensees may want to consider observations of biotic intrusion made during the post-closure observation and maintenance period when revising biotic intrusion assessment in future iterations of the performance assessment analysis. A licensee should develop an assessment of projected biotic intrusion after the post-closure observation and maintenance period based on the estimated evolution of the disposal site. The projection should not include land management practices that will be used during the institutional control period to limit the effects of biotic intrusion, unless those practices are passively effective after the institutional control period. Many engineered cover designs employ biointrusion barriers. If the licensee provides a technical basis for the barrier's passive performance, they can take credit for biointrusion barriers in the performance assessment projections. Analog information may be useful in supporting predictions of the performance of biointrusion barriers.

A qualitative assessment of the biotic enhanced release and its contributions to the dose may be sufficient depending on the site, its characteristics, and the characteristics of the waste disposed of at the site. In some cases, biological processes can strongly influence the release of radioactivity from LLW disposal facilities because the near-surface environment is biologically active.

In addition to direct release (e.g., uptake of radionuclides by deeply rooted vegetation), biota can indirectly enhance release when plants and animals modify the buried waste or the design of the LLW disposal facility in such a way that there is an increased potential for radionuclide release and transport. The following are examples of these processes:

- Burrowing animals or root systems develop tunnels or conduits that can enhance the transport of groundwater or increase gaseous release (e.g., bioturbation of a clay layer).
- Plant roots provide ligands that provide a source for radionuclides to bind, resulting in the formation of soluble radionuclide-organic complexes.
- Microbial degradation of the wasteforms leads to the enhanced generation of gases or creates waste materials that are more soluble and therefore more easily transported away from the site.
- Microbial enhanced degradation of waste containers or concrete vaults in a disposal system occurs.
- A drainage layer is plugged in an engineered cover system.
- Pedogenic processes can modify the soil properties of an evapotranspiration cover system.

These examples are not meant to be an exhaustive list; other biological processes may affect the performance of the waste disposal facility. The licensee should provide a technical basis for its consideration of biological processes on the performance of the disposal facility, including the basis for excluding biological processes from the evaluation.

3.3 Radionuclide Transport

This section of guidance focuses on assumptions, data, and models (conceptual and mathematical) that a licensee may use to develop a radionuclide transport model for the performance assessment. A licensee may use radionuclide transport modeling to estimate the transport of radionuclides in environmental media (e.g., waste, soil, air) to receptor locations (i.e., human access locations) over time. Radionuclides released from LLW disposal facilities (see Section 3.2) can be transported through the environment by groundwater, surface water (including suspended sediments), air, and biota (e.g., rodents, insects). Radionuclide doses may also be linked directly to the media themselves, such as the consumption of contaminated well water, or indirectly between pathways, such as the transfer of radionuclides from the groundwater to the surface water and ultimately to the pathways comprising the food chain.

The significant mechanisms of radionuclide transport from the LLW disposal facility to the environment accessible to the receptor should be identified and assessed by a licensee. Section 2.5.3 contains guidance on identifying and screening FEPs. Depending on the relevance of the FEPs, some disposal facilities will require detailed consideration of these features and processes in the performance assessment by licensees, whereas simplified analyses may be justified for other sites and disposal practices. Radionuclide transport models may need to be considered carefully for those facilities for which licensees take credit for significant delay in radionuclide migration from the disposal facility to the receptor and those for which there is little model support. A simplified analysis may be acceptable for facilities for which the simplified analysis can be shown to be clearly conservative or for which the simple model is well-supported by multiple lines of evidence, including field tests that demonstrate that the model and its parameters appropriately represent or bound site conditions.

The complexity of most sites and proposed disposal practices usually results in radionuclide transport models being developed on a site-specific basis. The radionuclide transport modeling process should appropriately account for temporal and spatial variability in the environmental transport pathways resulting from natural heterogeneity in environmental media and the evolution of site conditions over the analysis timeframe. Variability in natural systems is often scale-dependent. For instance, wind speeds may vary over a wide range of time scales (e.g., hourly, daily, annually). The level of variability considered should be consistent with the assessment context. In this case, the context is annual doses to an offsite receptor. It would be appropriate to consider how the scale-dependent variability may affect the outcome of the assessment through sensitivity analyses. If scale-dependent variability is found to be significant, a licensee may need to include short-term variability in the radionuclide transport modeling. For example, short-term variability may be considered when developing a distribution of wind speeds that could occur in any given year (in the above example), while longer-term variability may be treated as variability in the mean annual wind speed. The approach a licensee selects to represent the uncertainty and variability resulting from natural heterogeneities should not bias the outcome of the assessment such that radiological doses to an offsite receptor would be significantly underestimated. Licensees should document analyses supporting their conclusion that the treatment of uncertainty and variability in radionuclide transport abstractions does not result in biases that significantly underestimate radiological doses to an offsite receptor.

Licensees should ensure that the modeling of radionuclide transport is appropriately integrated in space and time with the source term releases (see Section 3.2). The radionuclide transport modeling should also be consistent with modeling of climate and infiltration, as well as the characteristics of the biosphere and the receptor (e.g., human access locations). Guidance on modeling of climate and infiltration is provided in Section 3.3.3 of NUREG-1573 (NRC, 2000a) and Section 4.3.1 of NUREG-1854 (NRC, 2007a). Guidance on biosphere characteristics and dose modeling appears in Section 3.4 of this document and in Section 3.3.7 of NUREG-1573 and Section 4.3.5 of NUREG-1854.

Section 2.2 of this document describes general technical considerations applicable to the development and review of a radionuclide transport model for a LLW disposal facility performance assessment. As mentioned previously, licensees and reviewers may also consult NUREG-1573, Section 3.3.6, for further guidance on transport modeling. Section 4.3.4 of NUREG-1854 may assist reviewers by providing technical considerations for acceptable radionuclide transport modeling. The following sections of this document provide specific guidance on aspects of radionuclide transport modeling in various environmental media.

3.3.1 Groundwater Transport

A licensee may perform groundwater transport modeling to assess the concentrations of radionuclides transported from LLW disposal facilities through the unsaturated and saturated zones. Groundwater transport is among the most likely processes for radionuclides to be transported from LLW disposal facilities. In addition to being a direct source of exposure to radionuclides, groundwater can transfer radionuclides to other exposure pathways that may ultimately result in doses to members of the public. These transfer processes include discharges to surface water through seeps and springs and vapor releases to the atmosphere.

A licensee may need to model the migration of radionuclides in groundwater and determine the contribution of the groundwater pathway to the total dose to the average member of the critical group. The complexity of hydrogeologic and geochemical conditions of the site may need to be reduced to form simplified representations of groundwater flow and transport. A licensee should provide a technical basis that the reduction in complexity has not resulted in the loss of information necessary to demonstrate that the performance objectives of Subpart C will be met.

Development of a groundwater transport model should consider relevant FEPs associated with the site (Section 2.5 presents guidance on FEPs). The characteristics of the wasteforms designed to limit releases of radionuclides as well as the physical characteristics of the site (e.g., hydrogeology, faults, and groundwater flow boundaries) should be considered by licensees. Physical and geochemical processes (e.g., advection, dispersion, diffusion, sorption, precipitation) are the primary phenomena included in radionuclide transport models.

The transport of radionuclides in groundwater can be affected by many different physical phenomena associated with the hydrogeology of the system, as well as by the physical components (e.g., engineered barriers) associated with the facility. Information on the hydrogeologic characteristics of the site including the stratigraphy, the existence of preferential pathways (e.g., fractures), spatial variations in properties, and anthropogenic features that may affect groundwater flow should be considered by licensees. Processes such as diffusion, mechanical dispersion, and colloid-facilitated transport should be considered. In the case of the unsaturated zone, variations in properties and features such as thickness of unsaturated strata and hydraulic properties can impact water flow. The spatial variation of hydrologic properties of aquifers and aquitards, as well as geologic features (e.g., fractures) and engineered structures (e.g., slurry walls), can influence groundwater flow velocities, gradients, volumes, and estimates of recharge to and discharge from the aquifers associated with the saturated zone. In addition, licensees should consider differences associated with the unsaturated zone and saturated zone. Flow of contaminants in the unsaturated zone may be strongly influenced by discrete features, such as fractures or other heterogeneities. A licensee should provide their site-specific characterization data of the spatial variation in hydrologic properties and geologic features. If site-specific information is not available, the licensee should demonstrate how variability in properties and features was incorporated and evaluated in the radionuclide transport modeling.

A licensee should evaluate the chemical characteristics of the groundwater and host rocks including sediments. Chemical processes such as sorption, precipitation, ion exchange, and redox reactions can affect radionuclide transport in groundwater. NUREG-1573 (NRC, 2000a) and NUREG-1854 (NRC, 2007a) provide guidance for assessing groundwater transport. Additionally, NCRP has published a summary of processes and parameters applicable to the development of groundwater transport models in the performance assessment for a LLW disposal facility (NCRP, 2005).

Table 3-1 summarizes site characteristics, physical processes, and geochemical processes that should be considered by licensees when developing groundwater transport models. Reviewers should use Table 3-1 to evaluate the scope of a licensee’s radionuclide transport modeling.

Modeling groundwater transport can be challenging for a variety of reasons. The characteristics and features that introduce challenges include the following:

- the complex interactions of the hydrologic, geologic, physical, and chemical processes associated with the system
- the site-specific flow and transport characteristics for modeling the initial release from the disposal facility (i.e., source term) through the unsaturated zone to the groundwater
- the limited availability of site-specific data to describe the FEPs for a specific groundwater system
- the natural heterogeneity of site characteristics associated with groundwater flow and transport and changes in characteristics over long times
- numerical analysis techniques may introduce modeling artifacts, such as numerical dispersion, which can bias results

A licensee should provide a description in sufficient detail of their radionuclide transport model to allow a reviewer to independently determine that the aforementioned challenges were adequately addressed. Some disposal facilities may require detailed consideration of these challenges in the groundwater transport model, whereas simplified analyses may be justified for other sites and disposal practices. The groundwater transport models may need to consider these site-specific complexities for (1) facilities for which licensees take credit for significant delay in radionuclide migration via groundwater from the disposal facility to the receptor, (2) those that take significant credit for reductions in concentration during transport, (3) those relied upon for defense-in-depth, and (4) those for which there is little model support.

Table 3-1 List of Parameters and Processes of Concern Associated with the Groundwater Transport Pathway

<u>Hydrogeologic Characteristics</u> Stratigraphy Geologic structures (e.g., faults) Ground-water flow boundaries Zones of groundwater recharge and discharge Soil and rock characteristics (e.g., porosity, texture, mineralogy) Fractures and fast pathways (i.e. discrete features) Quantity and quality of groundwater
<u>Physical Processes</u> Advection Dispersion Diffusion Deposition Radioactive decay and daughter ingrowth
<u>Geochemical Processes or Characteristics</u> Composition of groundwater Geochemical environment (e.g. pH, Eh, organic content) Sorption / Desorption Precipitation Complexation Resuspension Redox reactions Colloids
<u>Design Features</u> Well depth Screen length Physical components (i.e., engineered barriers)

A simplified analysis may be acceptable for facilities for which the simplified analysis can be shown to be clearly conservative or for which the simple model is supported by multiple lines of evidence, including field tests that demonstrate that the model and its parameters appropriately represent or bound site conditions. A simplified groundwater modeling approach may be sufficient to gain an adequate understanding of the FEPs associated with a specific system. More detailed groundwater flow and transport modeling, however, may be needed to identify important processes and assess the impacts of uncertainty and variability to support the simplification of the conceptual groundwater flow system.

An important consideration in modeling groundwater flow and transport is the inherent spatial variability of structural, physical, and chemical properties of the environmental media and the uncertainty in characterizing the spatial domain. Heterogeneity in flow and transport processes can vary over many orders of magnitude from the molecule scale to the basin scale (Ledoux and deMarsily, 1997). Some properties exhibit scale-dependence (e.g., dispersivity) (Neuman, 1990). When warranted by the significance of the transport pathway, a licensee may need to include a more explicit representation of the inherent variability. However, it is challenging to describe the full spectrum of the heterogeneity due to the amount of characterization that would be needed. Rubin (2003) summarized some approaches (e.g., estimation, simulation) that licensees may consider for use in representing the inherent variability and assessing its impact on groundwater flow and transport.

Licensees should demonstrate that the method used to assess groundwater transport does not bias the outcome such that radiological doses to an offsite receptor are significantly underestimated. A possible method to demonstrate this is through comparisons with viable alternative conceptual models of the groundwater flow system that are consistent with the current understanding of the site.

For the performance assessment of a LLW disposal facility, the parameterization of processes should be made at the scale (spatial and temporal) over which groundwater transport is evaluated. However, measurements of flow and transport parameters on these large scales are often not available or practical. Additionally, smaller scale measurements, such as from laboratory or field tests, can provide useful information to models, but the models can quickly become computationally complex. For instance, performance assessments often represent sorption of radionuclides on soils through the use of a distribution coefficient (K_d). In a groundwater transport abstraction for a disposal facility, this coefficient may be representing the inherent heterogeneities in the soil properties and groundwater chemistry over large spatial scales. In practice, distribution coefficients are often measured in the laboratory or field on a much smaller scale than what is modeled in the performance assessment and may not represent the actual heterogeneities in the groundwater pathway that the radionuclides might encounter. Therefore, licensees should consider approaches to demonstrate the appropriateness of model parameters for the scale of concern for the performance assessment (e.g., upscaling, inverse modeling). The following two sections provide examples of specific issues to consider when evaluating the unsaturated zone and the saturated zone.

3.3.1.1 *Modeling the Unsaturated Zone*

This section highlights issues specific to the flow and transport of groundwater through the unsaturated zone and the flow and transport modeling that affect the ability of a licensee to develop a defensible performance assessment. Section 4.3.4.2.3 of NUREG-1854 (NRC, 2007a) and NCRP-152 (NCRP, 2005) provide a general discussion of the issues that should be covered. Additional details regarding flow and transport in the unsaturated zone appear in other documents, including Bear (1979), Bear and Verruijt (1987), Domenico and Schwartz (1998), Evans et al. (2001), Faybishenko et al. (2000), Freeze and Cherry (1979), Hillel (1980), Looney and Falta (2000), NAS/NRC (2001), Nielsen et al. (1986), and Todd (1980). Documents such as NAS/NRC (1990) and NCRP (1984) discuss unsaturated flow and transport models. NRC-sponsored research related to the characterization and performance confirmation monitoring of the unsaturated zone is included in various references (Meyer et al., 1999; Rockhold, 1999; NRC, 1993b; NRC, 1999b; NRC, 1999c).

Modeling of flow and transport of radionuclides in the unsaturated zone provides a link between releases from an LLW disposal facility and the saturated zone. Key inputs for a licensee to consider when developing unsaturated zone flow and transport models include the infiltration rate and the release rate of radionuclides from the source; the resulting outputs, flow rate and radionuclide migration, are used as inputs when modeling saturated zone flow and transport.

Variations in soil characteristics and moisture content in the unsaturated zone as well as the complex relationships between hydraulic head, moisture content, and hydraulic conductivity can make modeling these systems difficult. Site-specific conditions can further influence modeling of the unsaturated zone. For example, at moist sites the disposal facility generally lies within a few meters or tens of meters of an underlying aquifer. The flow and transport of groundwater and radionuclides over this short distance may not be significant when assessing the overall performance of the site. Modeling the unsaturated zone for these types of sites may require only a simple approach such as not taking any credit for delay or dilution associated with the transport between the LLW disposal facility and the aquifer. At arid sites, however, the aquifer may lay several tens or even hundreds of meters below the disposal facility footprint. In this case the time required for radionuclides to reach the aquifer may allow for more physical and chemical interactions with the environment and significantly reduce the concentrations or the timing of when radionuclides reach the aquifer. As discussed in Section 2.2.3, model support is essential for providing a basis for a licensee's simulation results. Model support can be used to justify that the complexity (or lack thereof) in a licensee's model is appropriate. A licensee should demonstrate that 1) the complexity is necessary, 2) site-specific information is available to adequately characterize the complexity, and 3) model support is available to support the analysis results.

Arid sites may experience high evapotranspiration rates creating a situation where there is no communication or very limited communication between the disposal facility and the water table. This is especially true for the disposal of inventories containing primarily short-lived radionuclides. Modeling this situation is typically more complex than a traditional flow and transport analysis because spatial and temporal variability can more significantly impact the results. For either thin or thick unsaturated zones, discrete features such as fractures or abandoned wells can limit the effectiveness of the unsaturated zone as a barrier. Completion of field tests and analysis of field observations are recommended to reduce the uncertainty associated with discrete features in the unsaturated zone. Tracer studies over a large area can be effective.

Many of the processes that govern transport of radionuclides in the unsaturated (vadose) zone (i.e., advection, dispersion, and sorption (retardation)) are essentially the same as those that govern transport in the saturated zone. However, since the pore spaces of the vadose zone are only partially filled, the effective hydraulic properties have a nonlinear dependence on soil moisture content. Flow and moisture dependencies are commonly represented with moisture characteristics curves. Moisture characteristics curves can be difficult to define and to use to characterize the spatial variability over the area of a disposal site.

Because of the nonlinear relationships, flow in the unsaturated zone can be strongly influenced by extreme conditions (e.g., a zone of discrete features such as fractures, wetter years, or seasonal variations). Therefore, it is necessary for a licensee to understand how hydraulic conductivity changes as a function of the amount of moisture and the pressure in the soil. For example, when the fluid pressure is less than the atmospheric pressure, the pressure head is negative allowing suction to occur (Freeze and Cherry, 1979). Additionally, the infiltration rate may vary with time as a result of the intermittent nature of precipitation. It may also vary with the depth of the unsaturated zone, resulting in greater water content closer to the surface and dampening with depth.

Given these complexities, a graded approach that starts with the simplest and most conservative approach is recommended for licensees. This technique starts with a relatively simple representation of the system - assume homogeneous conditions and no time delay or dilution. Problems may arise with this simple approach for situations in which the unsaturated media are known to be highly structured or fractured, or if it is determined that there is significant time or distance to reach the saturated zone. For these cases, the modeling approach would need to be more complex. In general, a licensee should only include complexity if that complexity can be supported. However, in the iterative modeling process a licensee may need to add complexity to determine if the complexity is significant. If it is, support may need to be developed or a conservative approach may be necessary.

3.3.1.2 *Modeling the Saturated Zone*

In a performance assessment for a LLW disposal facility, a licensee should consider the flow of water through underlying aquifers and the phenomena that influence transport of radionuclides in groundwater. A licensee should have an adequate understanding of the input flux of radionuclides from the unsaturated zone. For example, although an increase in flow velocity into the saturated zone would appear to yield higher concentrations of radionuclides being released to offsite locations or other exposure pathways due to decreased travel time, it also results in a greater volume of water available to dilute radionuclide concentrations slowly percolating into the aquifer from the unsaturated zone. Thus, it is possible that the higher flow rate can actually result in a decrease in radionuclide concentrations. For a licensee to complete a sufficient evaluation of the groundwater transport in the saturated zone requires an understanding of the groundwater velocity field, radionuclide-specific release rates to the saturated zone, and the phenomena that influence the transport of radionuclides in groundwater (e.g., sorption, advection, diffusion, dispersion, and radioactive decay). Ultimately saturated-zone radionuclide concentrations are typically converted to two primary types of doses for receptor scenarios: the groundwater dose resulting from direct ingestion and the groundwater component of the dose resulting from ingestion of foodstuffs grown using contaminated water. Other pathways are possible and may be significant at specific sites though they are less common.

The velocity field provides a representation of the groundwater flow in the saturated zone. A velocity field, which is a function of location and time, is often derived using indirect, largely unmeasured, spatially variable, or unknown physical properties and boundary conditions that can be interpreted only subjectively. Licensees may develop the velocity field by using a site-specific model of the flow system that has been calibrated using site-specific data on hydraulic head. The hydraulic head can be obtained using monitoring wells and field experiments (e.g., slug tests). However, the derived velocity field is likely not going to be a unique representation for a specific site, as multiple velocity fields can often be used to describe a site equally well. As a result, licensees should provide justification and support for their assumptions. It is often useful for a licensee to include the uncertainty associated with the calibration and inverse modeling to derive groundwater flow fields in the performance assessment groundwater flow model. Therefore, the significance of the uncertainty can be directly assessed.

Licensees may describe groundwater flow in the saturated zone using a simplified flow equation, which combines Darcy's Law with the principle of conservation of mass. This approach may be further simplified by assuming a steady-state flow rate and uniform recharge to the aquifer over the spatial domain being considered. However, uncertainties such as the presence of heterogeneities in the system, variable or unknown boundary conditions, and scaling of data obtained from core samples to field conditions need to be evaluated by licensees when using this approach to groundwater flow modeling. A licensee must provide model support for the simplified flow model results.

Various other phenomena may influence the development of models to represent the transport of radionuclides in groundwater. Radioactive decay is well understood, presuming that there is sufficient understanding of the source term; however, approximations may be required when considering radioactive decay and ingrowth associated with disposal sites containing many radionuclides. For radionuclides with chain decay that results in multiple progeny, the behavior of the progeny in the environment may be substantially different than the behavior of the parent radionuclide (e.g., the K_d for Am-241 may be substantially different from the K_d for Np-237). In cases where a long-lived radionuclide has decay products of radiological significance, selecting the lowest plausible K_d value may not result in the highest estimated dose. A licensee should provide sufficient justification for the use of specific K_d values to evaluate sorption and desorption. Ideally, site-specific K_d values should be used. However, in cases where site-specific values are not available generic values may be assessed. Numerous publications have documented generic values; some even group distribution coefficients according to soil type (Sheppard and Thibault, 1990; Yu et al., 1993). Licensees should use these values with caution as they often include variation between sites but do not include potential measurement errors (e.g., exceeding solubility limits in measurements of sorption parameters). In addition, the measurements in the compilation may have been taken using significantly different techniques.

Ultimately, a licensee can best treat uncertainties associated with radionuclide transport in groundwater by using multiple conceptual models. This enables a licensee to examine the effects of different credible assumptions and provides a better understanding of which processes are most sensitive and may need to be considered in greater detail.

3.3.2 Surface Water Transport

Surface water transport modeling is used to assess the radionuclide concentrations in surface water (e.g., rivers, lakes) at human access locations at or beyond the site boundary. By demonstrating that the requirements for site suitability in 10 CFR 61.50, “Disposal Site Suitability Requirements for Land Disposal,” and site design in 10 CFR 61.51, “Disposal Site Design for Land Disposal” are met, it is unlikely that a licensee will estimate that significant amounts of surface water would directly intersect a waste disposal facility. Therefore, radionuclides will likely be transported from a LLW disposal facility via other pathways rather than a surface water pathway. However, radioactivity released to an aquifer may discharge to surface water bodies before contact with or use by the public. Mechanisms by which radionuclides may enter the surface water include groundwater discharge and deposition associated with atmospheric transport, and overland flow (e.g., associated with erosion).

Licensees should evaluate hydrological and chemical conditions at the site to form simplified representations of surface water flow and transport if surface water transport is a viable exposure pathway for public receptors. Simplified analyses to assess surface water transport may be justified at most disposal facilities sited and constructed according to 10 CFR Part 61 requirements. However, some facilities, depending on site-specific conditions, may require detailed consideration of surface water transport. Licensees should demonstrate that the method used to assess surface water transport does not bias the outcome such that radiological doses to an offsite receptor are significantly underestimated. A licensee should consider contributions to surface waters from other environmental media (e.g., groundwater seepage, atmospheric deposition, overland runoff, and erosion).

Radionuclides that are released to surface waters may be transported by a variety of processes including water flow, sediment transport, and bioturbation (Onishi, 2008). Radionuclides entering surface water systems may remain in solution, be suspended in the water column attached to particulates, or settle to the bottom and become associated with the sediments. Advection and dispersion are typically dominant processes, especially for soluble radionuclides in flowing water. Radionuclides that readily partition to suspended particles or sediments may also be significantly affected by sediment transport processes (e.g., deposition, erosion, bioturbation). Other hydrologic processes, such as turbulence and thermal and density stratification, can also affect the distribution of radionuclides in surface waters. The chemistry of the surface water, rocks, and sediments may affect the speciation or partitioning of radionuclides (e.g., due to sorption, precipitation, ion exchange, volatilization). Licensees should consider these phenomena when developing surface water transport models. Section 3.3.6.2 of NUREG-1573 provides guidance for the assessment of surface water transport (NRC, 2000a). Section 4.3.4.1.2 of NUREG-1854 provides guidance for the review of surface water transport abstractions (NRC, 2007a). Also, NCRP (1996a, 1996b) describes screening models that may be appropriate for many sites to determine whether more detailed modeling may be required. Additionally, NCRP (2005) and Onishi (2008) discuss approaches for modeling the transport of radionuclides in a variety of surface water bodies that may be appropriate depending on site-specific characteristics.

3.3.3 Atmospheric Transport

Atmospheric transport models estimate concentrations of radionuclides released to the atmosphere at offsite receptor locations. Section 3.2.6 discusses guidance for assessing the gaseous release of radionuclides (e.g., C-14, I-129, Kr-85, Rn-222, H-3) from the disposal facility to the atmosphere. Licensees may also need to evaluate the transport of particulate releases caused by direct release (e.g., wind erosion), if significant (see Section 3.2.7). Once released, radionuclides can be transported in the atmosphere to locations downwind from the disposal facility where they could contribute a nontrivial fraction of the dose to the average member of the critical group. To evaluate the impacts of gaseous radionuclides downwind from release points, licensees should consider the following FEPs (Crawford, et al., 2008):

- source characteristics (e.g., configuration of the release such as the release height from the surface, puff or continuous releases, gaseous or particulate)
- atmospheric transport processes (e.g., wind and turbulence)
- radionuclide removal mechanisms (e.g., rainfall, wet and dry deposition)
- general topography of the land near the disposal facility

Source characteristics listed above include information about the material released as well as the configuration of release. The characteristics of the released material include physical form (e.g., gaseous, particulate), chemical stability in the atmosphere, and radioactive decay. For instance, particles with diameters greater than 10 micrometers may experience significant gravitational settling, and thereby, possibly limited atmospheric transport. The configuration of the release may also be an important consideration. Information on the configuration includes timing and spatial extent. For instance, radioactivity may be released continuously or nearly instantaneously, as well as from a single point or over an area. Atmospheric transport processes listed above include a characterization of the physical processes affecting transport of radionuclides (e.g., advection, dispersion). These processes include movement by wind, represented by wind direction and speed, as well as mechanical and thermal turbulence which can result in mixing caused by eddies. Removal mechanisms listed above include deposition, as gases and particles are deposited on surfaces and possibly removed from the atmosphere. Deposition may result from a variety of processes, both dry and wet, including impingement, electrostatic interactions, chemical reactions, and rainfall. Site topography as well as nearby engineered structures could affect atmospheric transport; licensees should exercise caution when using analog atmospheric transport data for a site-specific evaluation.

An important consideration in atmospheric transport modeling is the scale of motion in atmospheric processes. Atmospheric processes such as wind direction and speed may vary over a wide range on spatial scales from a kilometer or less to thousands of kilometers, as well as over the course of hours to years. Therefore, the consideration of atmospheric transport processes and their parameterization is a function of the spatial and temporal transport scale of interest. Atmospheric transport from LLW disposal facilities to an offsite human receptor is typically on the order of less than a kilometer to tens of kilometers. Temporal scales of interest for LLW disposal range up to 10,000 years to assess the annual dose to an offsite receptor from releases. Licensees should consider processes consistent with the context of the transport scale, both spatially and temporally. Additionally, input data should be consistent with the scale of transport, both spatially and temporally. For instance, winds may vary in speed and direction with time and height. Therefore, meteorological data to support model parameterization should be consistent with and account for uncertainty and variability over the spatial and temporal scales of interest for the site. Licensees should demonstrate the representativeness of model parameters for the scales of concern for the performance assessment.

The assessment of the performance of some disposal facilities may require a licensee to evaluate the atmospheric transport of radionuclides associated with particulates. For instance, progeny of gaseous radon are charged and are attracted to atmospheric particles of opposite charge. Key factors for a licensee to consider when evaluating the transport of particulates include: mass loading, resuspension rate, deposition rate, and wind speed. These factors are dependent on site-specific conditions such as soil type, wind distribution, and other meteorological conditions, as well as mechanical disturbances.

The assessment of the performance of some disposal facilities may require detailed consideration of these processes in the atmospheric transport abstraction, whereas simplified analyses may be justified for other sites and disposal practices. The atmospheric transport models may need to consider these site-specific complexities for those facilities for which licensees take credit for significant delay in radionuclide migration via air transport from the disposal facility to the receptor, those that take credit for significant dilution, those that are relied upon for defense-in-depth protections, as well as those for which there is little model support. A simplified analysis may be acceptable for facilities for which the model can be shown to be clearly conservative or for which the simple model is well supported by multiple lines of evidence, including field tests demonstrating that the model and its parameters appropriately represent or bound site conditions. A simplified atmospheric transport modeling approach may be sufficient to gain an adequate understanding of the FEPs associated with a specific system. More detailed atmospheric transport modeling, however, may be necessary to identify important processes and assess the impacts of uncertainty and variability needed to support the simplification of atmospheric transport. Licensees should demonstrate that the methods used to assess atmospheric transport do not bias the outcome such that radiological doses to an offsite receptor are significantly underestimated.

NUREG-1573 provides a screening approach to assess whether more detailed consideration of atmospheric transport modeling is required for gaseous radionuclides (NRC, 2000a). Discussed in Section 3.3.6.3.2.1 of NUREG-1573, the approach uses the total gaseous radionuclide release over 1 year and conservative meteorological conditions for wind speed, atmospheric stability, and atmospheric diffusion. However, the licensee should still provide justification for the conservatism of the meteorological assumptions and parameters used. NCRP-152 discusses possible approaches for estimating quantities of particulates suspended in the air (NCRP, 2005). An NRC staff-recommended screening approach to evaluate the transport of particulate matter, which is suspended in the air and transported downwind, assumes that the radionuclide concentrations in the atmosphere are equal to the concentrations in the surface soil or other source from which they originated. Section 3.3.6.3.2.2 of NUREG-1573 provides guidance for sites where more detailed analyses may be required. In addition, Crawford et al. (2008), discusses models that have been developed to assess atmospheric transport of radionuclides. Licensees should be aware that the output of the models is dependent on their assumptions and the data to support the parameters. Model selection and parameterization should be consistent with site conditions and supported by field observations, laboratory experiments, and other relevant information.

3.3.4 Biotic Transport

This section defines biotic transport as the transport of radionuclides from a disposal facility via biota (NRC, 1982d). Other sections of this document cover the indirect effects of biota on the disposal system, such as damage of an engineered cover by burrowing animals. This biotic transport section does not cover plant uptake or radionuclide movement within the biosphere after radionuclides have been released from the disposal facility via other mechanisms, such as groundwater release. Instead, this section focuses on offsite transport of radionuclides that have been released from the disposal facility by biota. One example of intrusion and active transport involves the Russian thistle (tumbleweed or *Salsola kali*). The long root system (on the order of meters) allows the plant to take up radionuclides from the soil (i.e., biota enhanced release). In autumn, the mature plant dries and detaches from the surface; it is then blown by the wind until it encounters an obstruction (biotic transport). Thus, the plant can cause both vertical and horizontal movement of radioactive material from a disposal site.

A qualitative assessment of the biotic transport pathway and its contributions to the dose may be sufficient depending on the site, its characteristics, and the characteristics of the waste disposed of at the site. Biotic transport may be the primary transport mechanism at sites without viable water pathways.

Secondary transport occurs after transfer of radionuclides to biotic sources (i.e., plants and animals) such as the movement of radionuclides within and among the plants and animals associated with the food chain. Examples of processes that transfer radionuclides to biotic sources include overland flow, atmospheric deposition, and use of contaminated groundwater for irrigation. Overland flow can result in the deposition of radionuclides into a surface water body. Once deposited, radionuclides can remain in the water where they may be taken up by animals drinking the water or by plants extracting water through their root systems; radionuclides settling to the bottom sediments may be extracted by plant root systems. Additionally, radionuclides released to the atmosphere may accumulate on plant surfaces or in the soil by wet or dry deposition and eventually become incorporated in plants and animals. The groundwater transport pathway is often the most common means for transporting radionuclides from LLW disposal facilities to the surrounding biota since the waste is buried below ground. Secondary transport allows for additional displacement of radionuclides available to the biota. Food chain activities, such as the consumption of fruits containing radionuclides by animals, are an example of secondary transport. Upon entering the food chain, processes such as ingestion and excretion provide a means for the movement of radionuclides throughout the system. Secondary transport is evaluated using modeling of the biosphere.

3.4 Biosphere

For the purposes of a performance assessment, the biosphere is the physical environment accessed by a receptor. The objective of biosphere modeling is to calculate estimates of radiological exposures to humans, in terms of the average member of the critical group, from radionuclide releases from the disposal site over time and space. Licensees can then use the resultant exposures for comparison with the 10 CFR 61.41 performance objective. The biosphere includes the transfer of radionuclides through the human food chain and human dosimetry, including characteristics and lifestyles of the human receptors. There are two specific areas to consider in the assessment of doses to humans. First, the mechanism of radionuclide transfer through the biosphere to humans needs to be identified and modeled. This is often termed pathway analysis. Second, the dosimetry of the exposed individual must be modeled. This is termed the dose assessment. Section 3.3.7 of NUREG-1573 discusses pathway analysis and dose assessment in detail and provides acceptable approaches for performing these analyses (NRC, 2000a).

The pathways analysis and dose assessment require the development of receptor scenarios that describe the activities in which an average member of the critical group would be engaged. Receptor scenarios typically involve input parameters to describe the transport and exposure to radionuclides that can be generally classified as behavioral, metabolic, or physical. Behavioral parameters collectively describe the behavior hypothesized for the average member of the critical group. The behavior is normally consistent with local practices (e.g., time spent gardening, vegetable consumption rates). Metabolic parameters also describe the exposed individual, but generally address involuntary physiological characteristics of the individual (e.g., breathing rates, factors converting intake of unit activity to dose by radionuclide). Physical parameters collectively describe the physical characteristics of the site (e.g., geological, hydrologic, geochemical, ecological, and meteorlogic inputs). Section 4.3.5 of NUREG-1854 provides guidance on behavioral, metabolic, and physical input parameters used in the biosphere modeling (NRC, 2007a).

For estimating the performance of a land disposal facility far into the future, licensees may need to consider changes to the physical environment over time and the impact that may have on receptor behaviors or physical parameters of the site. For instance, at a site that is currently inhospitable to gardening because of a harsh environment, a licensee may need to consider the evolution of the environment over time. If future climates are expected that may significantly change human behaviors, licensees may need to consider behaviors conducted at other sites that are currently analogous to the expected climate. Because metabolic parameters are involuntary and future evolution of humans is difficult to estimate, licensees should rely on current information regarding metabolic parameters and do not need to forecast changes to metabolic parameters over long timeframes.

4.0 INADVERTENT INTRUSION

Section 61.23(c) specifies the standard that must be met to protect individuals who could occupy the disposal site after closure and unknowingly be exposed to radiation from the waste (i.e., inadvertent intruders as defined in 10 CFR 61.2). The requirement does not apply to protection of individuals who may knowingly or deliberately recognize that a radiation hazard exists and choose to ignore the hazard. The standard states that applicants should provide reasonable assurance that individual inadvertent intruders would be protected in accordance with the performance objective in 10 CFR 61.42. Section 61.13 specifies the technical analyses to demonstrate compliance with the performance objectives in Subpart C.

Figure 4-1 illustrates the three analyses necessary to demonstrate compliance with 10 CFR 61.13(b). To protect inadvertent intruders, the analyses require demonstration that (1) waste acceptance criteria developed in accordance with 10 CFR 61.58 will be met, (2) adequate barriers to inadvertent intrusion will be provided, and (3) exposures to any inadvertent intruder will not exceed the limits specified in 10 CFR 61.42 as part of an intruder assessment.

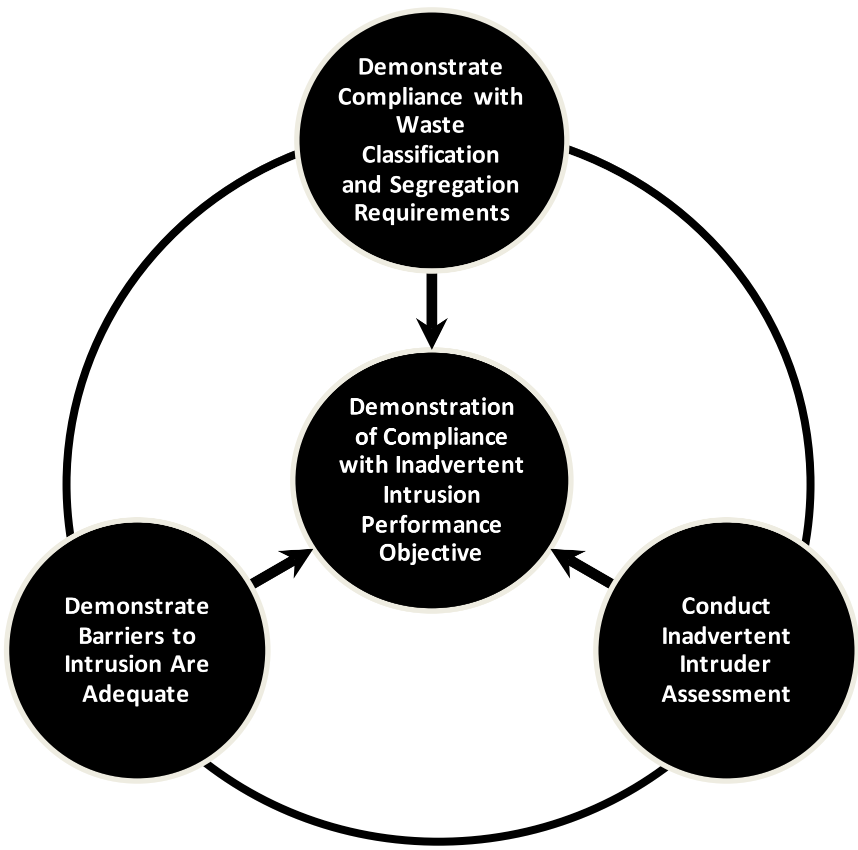


Figure 4-1 Technical Analyses Required to Demonstrate Compliance with the 10 CFR Part 61 Performance Objective for the Protection of Individuals from Inadvertent Intrusion

This section describes the information that a licensee should provide and a reviewer should evaluate with respect to the technical analyses for inadvertent intrusion. Section 4.1 describes information that should be provided to support a demonstration that the waste acceptance criteria will be met. Section 4.2 describes information needed to demonstrate that barriers to inadvertent intrusion will be adequate. Section 4.3 describes information that should be provided as part of an intruder assessment to demonstrate that exposures to any inadvertent intruder not exceed the limits specified in 10 CFR 61.42.

4.1 Waste Acceptance Requirements

Requirements for waste acceptance for land disposal appear at 10 CFR 61.58. The regulations require applicants to identify (i) criteria for the acceptance of waste for disposal, (ii) acceptable methods for characterizing the waste, and (iii) a program to certify that waste meets the acceptance criteria prior to receipt at the disposal facility. Section 9.0 of this guidance document describes acceptable approaches for demonstrating compliance with the waste acceptance requirements specified at 10 CFR 61.58. Licensees who limit disposal to waste under approved waste acceptance plans satisfy this requirement.

Reviewers should coordinate the review of whether the waste acceptance criteria will be met with reviews of the waste acceptance requirements. See Section 9.0 for guidance on reviewing compliance with the waste acceptance requirements. This review should include (1) an assessment of whether the waste acceptance criteria are adequate, and (2) confirmation that the licensee has identified acceptable methods for waste characterization and has an adequate waste certification program to demonstrate that the acceptance criteria are met.

4.2 Inadvertent Intrusion Barriers

Intruder barriers are designed to inhibit contact with the waste (e.g., Class C waste) that is expected to present a hazard to an inadvertent intruder should institutional controls fail. The barriers ensure that radiation exposures to an inadvertent intruder will be within the limits of the performance objective specified at 10 CFR 61.42. Intruder barriers are distinct from institutional controls, yet complement the protection provided by institutional controls as a measure of defense-in-depth. An intruder barrier is defined as (1) a sufficient depth of cover over the waste that inhibits contact with waste and helps to ensure that radiation exposures to an inadvertent intruder will meet the performance objective, or (2) engineered structures that provide equivalent protection to the inadvertent intruder. Section 61.52(a)(2) requires that wastes designated as Class C must be disposed of with sufficient depth (i.e., minimum of 5 meters below the surface of the cover) or intruder barriers designed to protect for at least 500 years. Licensees who elect to develop waste acceptance criteria from the results of the technical analyses (i.e., 10 CFR 61.13) may also need to identify certain waste streams that require intruder barriers to ensure protection of an inadvertent intruder. The inadvertent intruder assessment should be used to demonstrate that the intruder barrier can limit exposures for at least 500 years when used for Class C waste, or as long as necessary to limit exposures to an inadvertent intruder to the limits prescribed in 10 CFR 61.42. The assessment should look at site-specific conditions such as the length of time over which the disposed waste presents a significant hazard to an inadvertent intruder. Further, the inadvertent intruder assessment may identify the need for adequate barriers to demonstrate protection of inadvertent intruders from disposal of other waste (e.g., Class A and B waste) based on site-specific conditions.

While both intruder barriers and institutional controls can limit contact with the waste, they use different mechanisms. Institutional controls are used to limit intruder access to, or use of, the site for a period of time following transfer of the disposal site to the owner and cannot be relied on for more than 100 years under 10 CFR 61.59, "Institutional Requirements." An institutional control program includes legal mechanisms (e.g., land use restrictions), environmental monitoring, periodic surveillance, minor custodial care, or other requirements as determined by the Commission as well as the administration of funds to cover the costs of these activities.

Intruder barriers are passive features of the disposal facility and site that are intended to enhance a disposal facility's ability to protect an inadvertent intruder who may engage in normal activities or other reasonably foreseeable pursuits that are consistent with activities in and around the site at the time of closure. Intruder barriers may include sufficient depth of cover over the waste or engineered structures (e.g., reinforced concrete vaults) that can provide protection to the inadvertent intruder. For more mobile radionuclides that could affect the intruder through ground water exposure pathways, intruder barriers may also include features that limit the potential release and transport of radionuclides (e.g., the wasteform).

Section 61.12(b) requires that the specific technical information describing the land disposal facility include design features related to inadvertent intrusion. As part of this description, licensees should identify intruder barriers and describe their capabilities in terms of inhibiting contact with disposed waste and ensuring that radiation exposures will meet the performance objective at 10 CFR 61.42. Because of the wide range of radioactive materials at disposal facilities, the regulations and this guidance are not prescriptive as to the acceptability of site-specific intruder barriers. Because of this flexibility and because intruder barriers are site-specific, it is important for licensees to clearly and completely document the description of the barriers' capabilities and the supporting technical basis.

The information supporting the barriers' capabilities should be provided for the time period over which each barrier performs its intended function, including any potential changes to the barrier during the compliance period. These capabilities, including uncertainties, should be consistent with the performance attributed to the barriers in the analyses performed in the inadvertent intruder assessment. The NRC staff will use information gained from the inadvertent intruder assessment, independent calculations, and other appropriate quantitative analyses to confirm each barrier's capabilities. The NRC staff will confirm that the technical bases for barrier capabilities are consistent with the technical bases for the inadvertent intruder assessment. In some cases, the barrier capabilities may differ from the information used to support the intruder assessment; for example, the intruder assessment may have conservatively ignored the benefits of the intruder barrier.

The functionality and robustness of the barriers will be determined using the risk-informed graded approach described in Section 4.2.1 and will be evaluated on a site-specific basis for each license application. However, the general framework that a licensee should consider will not vary from licensee to licensee; only the depth and breadth of information supplied to demonstrate the capabilities of the intruder barriers may vary. The guidance that follows provides the general framework a licensee should consider for intruder barriers.

4.2.1 Risk-Informed Approach to Evaluating Intruder Barriers

Licensees are encouraged to use a risk-informed approach to select, design, and provide a technical basis for the intruder barrier(s) at a specific site. The approach is defined by the hazard level and likelihood of hazard occurrence. More robust barriers and additional bases for barrier capability should be provided for higher risk disposal facilities compared to lower risk facilities. The use of the term "risk" with respect to intruder barriers means the potential for risk; the analyses and resultant actions should ensure that high risks are not realized by a member of the public. The NRC would consider disposal facilities where the potential intruder hazards may be large as high risk. For instance, the NRC would consider a disposal facility with unmitigated doses following the institutional control period greater than 50 mSv/yr (5,000 mrem/yr) to be high risk.

Licensees should assess the significance of each intruder barrier to mitigate exposures to inadvertent intruders. Any intruder barrier that reduces unmitigated doses less than or equal to 5 mSv/yr (500 mrem/yr) to smaller doses is of low significance. A barrier that reduces unmitigated doses ranging between 5 to 50 mSv/yr (500 to 5,000 mrem/yr) to less than 5 mSv/yr (500 mrem/yr), and results in a relative reduction of 50 percent or more, is of moderate significance. A barrier that reduces unmitigated doses greater than 50 mSv/yr (5,000 mrem/yr) to less than 5 mSv/yr (500 mrem/yr) is of high significance. Licensees should provide a technical basis for the capabilities of the barriers commensurate with their significance in mitigating inadvertent intruder exposures. The technical basis should evaluate the time period over which each barrier performs its intended function including any changes during the various periods of performance (i.e., compliance, protective assurance, and performance periods).

Reviewers will use insights from a licensee's understanding of each barrier's capabilities as well as independent analyses to focus reviews on the technical basis supporting the capabilities of significant barriers to limit contact with the waste and their integration in the inadvertent intruder assessment. Section 4.3 discusses guidance on the inadvertent intruder assessment.

4.2.2 Technical Basis for Intruder Barrier Capabilities

There is significant uncertainty concerning the estimation of service life and long-term degradation of intruder barriers. This section provides guidance on the main elements of information that should be provided to support the technical basis for the evaluation of intruder barrier capabilities, including the following:

- a full description of the design, features, and functionality of the intruder barriers
- a full description of the site and environmental conditions an intruder barrier would be exposed to
- a description of potential degradation mechanisms including consideration of combined and synergistic effects resulting from the service environment expected for the barriers
- a description of the suitability of selected numerical models, if used, for the estimation of intruder barrier capabilities
- an estimation of uncertainty in parameters and models used in the assessment of barrier capabilities and the design of intruder barriers

- parametric or component sensitivity analysis to identify how much degradation of the intruder barrier is needed for noncompliance to occur
- model support for the intruder barrier performance (e.g., analogs, experiments, simple engineering calculations to demonstrate the reasonableness of the results)
- QA and QC for the design, analysis, and implementation of intruder barriers

The capabilities of some intruder barriers may not be amenable to validation in the traditional scientific sense because of the long time periods involved. Therefore, licensees should provide multiple lines of evidence particularly, though not exclusively, to support barrier capabilities beyond 500 years. As discussed in Section 2.2.3, model support can come in many different forms, including but not limited to analogs, laboratory experiments, field experiments, formal and informal expert judgment, and engineering calculations to demonstrate the reasonableness of the results (e.g., hand calculations when numerical models are used). The level of model support should be commensurate with the relative significance of the barriers in protecting the inadvertent intruder. Section 2.2.3 presents more detail on model support.

During the operational, postclosure observation and maintenance, or institutional control periods monitoring may be needed to verify the capabilities of intruder barriers. This monitoring involves both monitoring aspects of the environmental system surrounding the disposal facility and monitoring the performance of the facility itself. Nondestructive monitoring technologies that include designed and emplaced sensors are preferred to conventional post-failure monitoring. To the extent practicable, intruder barriers should be designed to support and simplify monitoring and maintenance.

Reviewers should use information from a licensee's description of intruder barrier capabilities to focus their review of the adequacy of the technical bases. Reviewers should confirm that the technical bases are commensurate with the significance of each barrier's capability and the associated uncertainties. Based on their reviews of the inadvertent intruder assessment, reviewers should confirm: (1) the consistency of the technical basis with the intruder assessment and (2) the quality and completeness of the technical basis for the barrier capabilities.

4.2.3 Use of Engineered Intruder Barriers

If an engineered intruder barrier is used at a disposal facility, only the barrier's passive performance to inhibit contact with the waste and limit radiological exposures (i.e., performance of the barrier without monitoring, inspection, and maintenance) should be credited in the intruder assessment to demonstrate compliance with the performance objective at 10 CFR 61.42. The assessment of the capabilities of the engineered intruder barrier should consider the reasonableness of a breach and the potential degradation of the barrier over time because monitoring and maintenance cannot be relied on beyond the period of institutional control. Licensees can find additional information about intruder barriers in:

- NUREG-1757, Revision 1, Volume 2, Section 3.5.4 and Appendix P (NRC, 2006). These sections discuss degradation mechanisms and capabilities of common engineered barriers in greater detail.

- NUREG-1757, Revision 1, Volume 2, Section 3.5.5. This section summarizes existing guidance and references that may have some relevance to the application of engineered intruder barriers at disposal facilities.
- NUREG/CP-0195 (NRC, 2011a). This document includes reference material and electronic information sources in the appendices.

Other reasonably foreseeable disruptive events caused by humans or natural events and processes should be evaluated, and uncertainty in projecting the passive performance of the barriers into the future should be considered (see Example 4.1). For example, waste and disposal facilities might also be subject to instability because of waste characteristics (e.g., differential settling caused by voids in the waste) or facility design (e.g., long-term physical instability of covers). Subsidence could have the following effects on an engineered surface cover: small depressions forming on the cover, differential settlement causing an uneven cover surface, stress cracks forming on the cover surface, and open voids in the cover, each of which could reduce the depth of cover to an insufficient thickness.

Example 4.1

A licensee proposes to use a reinforced concrete vault to limit access to the waste by an inadvertent intruder drilling into the waste. The concrete vault would function as a barrier for as long as it maintains its integrity.

Conclusion: The licensee should consider the effect of reasonably foreseeable processes on the degradation of the vault's mechanical properties that would be relied on to limit access to the waste. These processes, which are site-specific, could include seismic activity, cementitious material degradation such as sulfate attack, carbonation, leaching of the cement, and corrosion of the reinforcing steel. The licensee should also consider local drilling practices and estimate when currently used technology would likely penetrate the vault given its estimated degradation of mechanical properties. For instance, the likelihood of breaching the concrete vault would likely occur earlier in regions of the country where hard-rock drilling is common than in regions where hard-rock drilling is not common. Local drilling practices vary across geographic regions. Over long periods of time, the assumption of only locally-used technology in the geographic region of interest may not be appropriate. At a minimum, licensees should communicate the results if drilling were to occur, even if drilling is not anticipated based on locally-used technology.

Frequently, engineered surface covers rely on vegetation to resist erosion. The probability that the vegetation cover will deteriorate, due to future drought or disease, is dependent on the hardiness and diversity of plants established on the cover. Fires, severe storms, and ecological succession, due to changing temperature and precipitation, could influence the ability of the vegetation to resist wind and water erosion and maintain a sufficient depth of cover over the waste. Over long periods of time, a minimum erosion rate can amount to a substantial thickness of cover loss (e.g., a 0.5 millimeter (mm)/yr rate will reduce a cover's thickness by half a meter in 1,000 years).

4.3 Inadvertent Intrusion Assessment

The regulations at 10 CFR 61.13 require an inadvertent intruder assessment to demonstrate that exposures to an inadvertent intruder will not exceed the objectives specified in 10 CFR 61.42. The primary objective of an inadvertent intruder assessment is to quantitatively analyze the potential radiological exposures to any individual who is assumed to occupy the site at some time after the loss of institutional controls. The intruder then engages in normal activities on site, such as agriculture, dwelling construction, resource exploration (e.g., drilling), or other reasonably foreseeable pursuits that are consistent with activities in and around the site at the time of closure, in which the person might be unknowingly exposed to radiation from the waste.

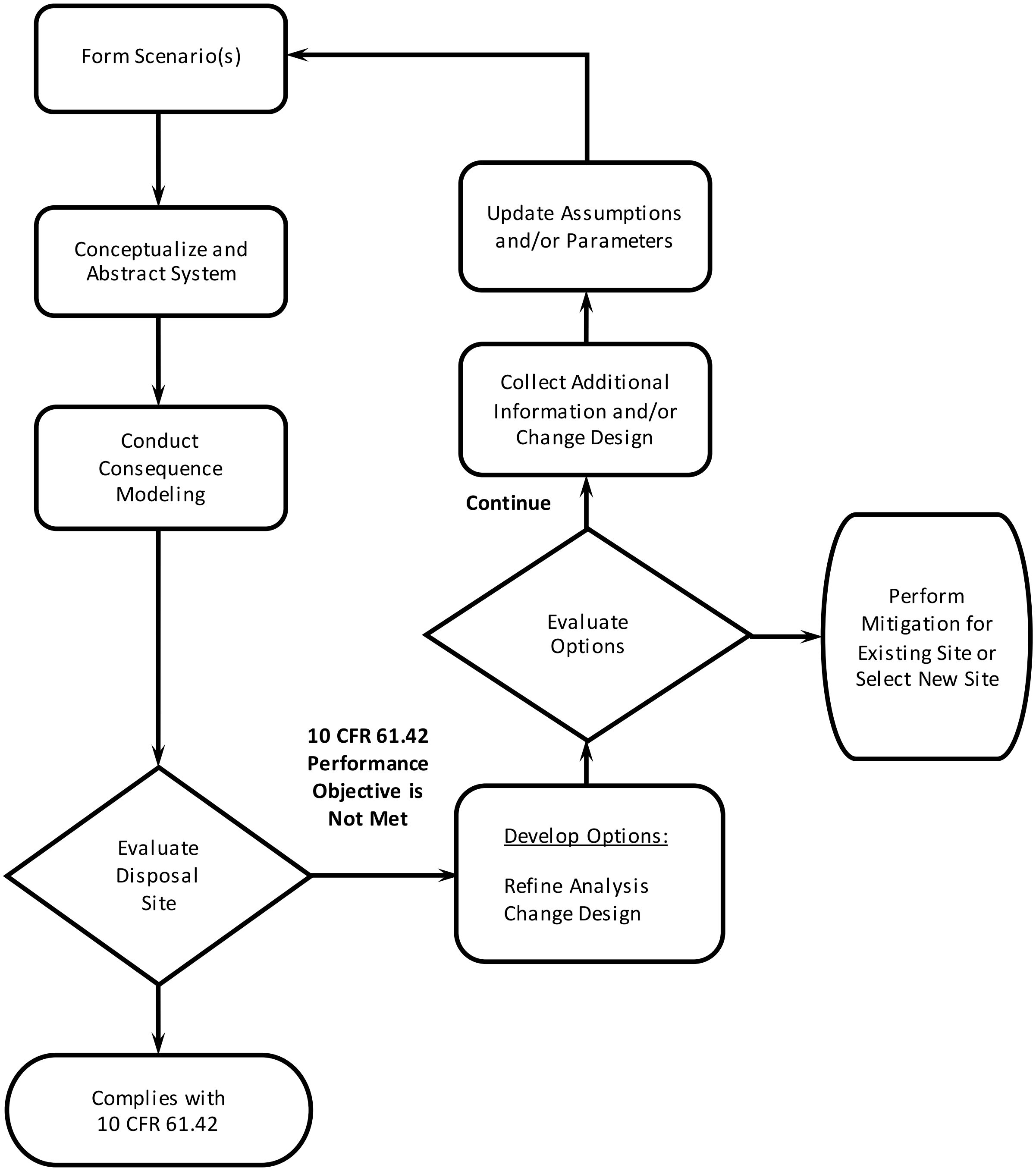
The process for conducting an inadvertent intruder assessment, as shown in Figure 4-2, is similar to the process for conducting a performance assessment in that it is designed to evaluate the following questions, often referred to as the risk triplet:

- What could occur?
- How likely is it to occur?
- What are the consequences?

Inadvertent intrusion assessment is an iterative process involving site-specific, prospective modeling evaluations of potential radiological consequences as a result of reasonably foreseeable human activities that might unknowingly occur should an individual occupy a near-surface disposal facility for LLW after the loss of institutional controls. An intruder assessment has two primary objectives:

- To determine whether reasonable assurance of compliance with the performance objective for protection of inadvertent intruders can be demonstrated
- To identify insights that support additional site-specific design and control measures to preclude the intrusion or to limit radiological impacts to acceptable levels from disposed waste should an inadvertent intrusion occur

1



2

3 **Figure 4-2 Example of an Inadvertent Intruder Assessment Process Required Per**
4 **10 CFR 61.42**

Inadvertent intrusion is expected only if required institutional controls or societal memory are lost. Because of these protections, inadvertent intrusion is considered unlikely. However, as time passes after closure of the disposal facility, institutional controls or societal memory cannot be assured and inadvertent intrusion may be possible. Thus, Section 61.59 requires that the time period over which institutional controls can be relied on may not be more than 100 years following transfer of control to the disposal site owner.

Further, there is no scientific basis for quantitatively predicting the nature or probability of a future disruptive human activity over long timeframes. This is in contrast to a natural process for which a scientific basis may be developed to support a probability of occurrence. Therefore, an inadvertent intruder assessment does not consider the probability of inadvertent intrusion occurring. Rather, the assessment assumes that reasonably bounding receptor scenarios occur and evaluates the radiological consequences that could be experienced by inadvertent intruders should institutional controls or societal memory be lost (NCRP, 2005).

The approach to evaluating the first two questions of the risk triplet is an important difference between an inadvertent intruder assessment and a performance assessment and a key reason why the regulations in 10 CFR Part 61 treat these two types of assessments separately. Intruder assessments qualitatively consider the likelihood of a disturbance of the disposal site induced by human intrusion after a loss of institutional control for the reasons mentioned in the preceding paragraph. In contrast, offsite exposures to the general population are driven by natural processes, such as those evaluated in a performance assessment, and could occur at any time after disposal. The performance assessment does not assume that institutional controls or societal memory would be lost (NCRP, 2005). Performance assessments can, therefore, quantitatively evaluate the likelihood of natural events or processes and their effect on the performance of a disposal facility to limit radiological consequences to members of the public beyond the site boundary. The intruder dose assessment is more strongly tied to specific future human behaviors.

Given the qualitative assumption that inadvertent intrusion is unlikely, albeit possible, because of the presence of required institutional controls, a secondary objective of the assessment is to provide insights that support additional site-specific design and control measures to preclude the intrusion or to limit radiological impacts to acceptable levels should an inadvertent intrusion occur. The additional measures could include site-specific inventory limits or other mitigation techniques such as additional intruder barriers or enhanced disposal practices. See Section 7.0 of this document for additional guidance on defining inventory limits based on the results of the technical analyses, including the inadvertent intruder assessment.

As with the performance assessment, scenario analysis and model abstraction are also key attributes of an inadvertent intruder assessment. Scenario analysis identifies, screens, and constructs scenarios from relevant FEPs for the disposal facility. For an intruder assessment, the formation of scenarios is focused on identifying reasonably foreseeable activities that an inadvertent intruder might engage in on the site (i.e., receptor scenarios). In the near term, licensees can assess reasonably foreseeable human activities based on site-specific conditions. However, future human activities are uncertain at longer times. Therefore, 10 CFR Part 61 requires that licensees assess normal activities, such as agriculture or dwelling construction, or pursuits that are consistent with activities in and around the site at the time of closure to limit excessive speculation about future human activities far into the future regardless of whether the intruder activities and the potential pathways of radiological exposure are likely to be affected by features and processes relating to or affecting the facility design and site characteristics over the various periods of performance (e.g., the presence of intruder barriers and their degradation, future climate conditions). Section 2.5.3 discusses methods to identify and screen FEPs for the compliance and protective assurance periods. The approaches are also generally appropriate for the inadvertent intrusion assessment.

Reviewers should use insights drawn from the review of the intruder barrier analysis (see Section 4.2) to focus their review on topics within the intruder assessment that are important to inhibiting contact with the waste or ensuring that potential radiation exposures to an inadvertent intruder will meet the 10 CFR 61.42 performance objective. The following sections provide guidance related to the process for conducting site-specific inadvertent intrusion assessments. Section 4.3.1 provides guidance on forming receptor scenarios for use in the assessments. Section 4.3.2 provides guidance related to specific aspects of modeling radiological consequences for assumed inadvertent human intrusion. When reviewing a licensee's inadvertent intruder assessment, reviewers should also consult Section 2.0 for guidance on general considerations regarding scenario analysis, model abstraction, and performance assessment that were highlighted in the preceding paragraphs. Section 9.0 also discusses other considerations related to developing waste acceptance criteria from the technical analyses (e.g., using the information from intrusion assessments to establish site-specific measures to limit radiological impacts if inadvertent intrusion occurs).

4.3.1 Receptor Scenario Analysis

In developing 10 CFR Part 61, the NRC staff recognized that it is unlikely, though possible, that an individual will occupy a site after closure because of the presence of institutional controls. 10 CFR Part 61 does not specify that a particular intrusion scenario be used in the assessment to demonstrate compliance with the performance objective for protection of inadvertent intruders. Rather, the criteria are performance-based. Thus, various methods, both generic and site-specific, are available to licensees, to demonstrate compliance with the criteria.

Scenario analysis addresses the following questions pertinent to inadvertent intrusion:

- What human activities are reasonably foreseeable in the vicinity of the land disposal facility?
- How can an intruder unknowingly come in direct contact with the disposed waste or be exposed to its radiation?
- How does the radioactive material move through the environment on the site?
- What are the inadvertent intruder's habits that will determine exposure?

Intruder receptor scenarios are defined as reasonable sets of activities related to the future use of the site. Therefore, receptor scenarios describe potential future land uses, human activities, and behavior of the engineering design and natural setting. In most situations, possible scenarios for intruders to interact with or be exposed to radiation from the disposed waste are numerous. The criteria in 10 CFR Part 61 do not require an investigation of all possible receptor scenarios; their focus is on reasonably foreseeable activities of the inadvertent intruder. Licensees do not need to assess inadvertent intruder activities that are considered implausible because of persistent physical constraints at the site. The inadvertent intruder is defined in 10 CFR 61.2 as "…a person who might occupy the disposal site after closure and engage in normal activities, such as agriculture, dwelling construction, or other pursuits in which the person might unknowingly expose the person to radiation from the waste included in or generated from a disposal facility." Assessment of receptor scenarios for an inadvertent intruder should focus on those activities from which the inadvertent intruder would reasonably be expected to receive the greatest exposure to radiation from the waste. Because of the uncertainty in human activities far into the future, the NRC staff recommends a suite of generic receptor scenarios that are associated with normal activities, described in Section 4.3.1.1, to represent reasonably foreseeable inadvertent intruder activities. Licensees are also permitted to use site-specific scenarios based on other reasonably foreseeable pursuits that are consistent with activities in and around the site at the time of closure to limit speculation about future human activities. Guidance on developing site specific scenarios is discussed in Section 4.3.1.2. These sections use a number of different terms describing receptor scenarios. Table 4-1 includes a description and comparison of these receptor scenario terms.

The definition of receptor scenarios and the intruder assessment can be generic or site-specific. Regardless of the specific method used to develop receptor scenarios, the licensee should provide sufficient justification for its approach. Licensees may use generic receptor scenarios similar to those described in NUREG-0782 (NRC, 1981a) with site-specific waste streams, or they may develop site-specific receptor scenarios to evaluate site-specific waste streams. Site-specific receptor scenarios may be developed by modifying the exposure pathways included in the generic receptor scenarios or may be constructed based on waste characteristics, disposal practices, site characteristics, and, when appropriate, projected land use.

The NRC staff continues to view the generic receptor scenarios as reasonably conservative for estimating potential radiological exposures to an inadvertent intruder while limiting excessive speculation about future human activities. These receptor scenarios are normal activities that humans typically engage in, in a variety of environments, and they contain a nearly comprehensive set of exposure pathways reflecting the generic nature of the original analysis for the development of 10 CFR Part 61 (NRC, 1981a). Licensees may use the generic receptor scenarios described in Section 4.3.1.1 in an intruder assessment to demonstrate compliance with 10 CFR 61.42 for site-specific waste streams. However, in some cases generic receptor scenarios may need to be modified based on site-specific conditions (e.g., waste streams, facility designs, or environmental conditions) to demonstrate compliance with the inadvertent intruder performance objective.

Depending on the method used, licensees should provide justification for their selections. For some licensees, this may require minimal site-specific data to support the assumptions inherent in the generic receptor scenarios or for removal of specific exposure pathways. Other licensees may need to thoroughly investigate and justify the appropriateness of the selected receptor scenarios, which may include an evaluation of alternate receptor scenarios. If a licensee creates a receptor scenario based on site-specific conditions, they should provide transparent and traceable documentation of the justification for each assumption used in developing the receptor scenario (e.g., justify the inclusion (or exclusion) of a particular exposure pathway).

Table 4-1 Comparison and Description of Intruder Receptor Scenario Terms Used in this Guidance

Types of Scenarios		Evaluation Purpose	Description
Plausible	Generic	All can be used to demonstrate compliance with the inadvertent intruder performance objective.	The scenarios used to inform the waste classification criteria at 10 CFR 61.55 that are consistent with normal activities including agriculture, dwelling construction, resource exploration or exploitation.
	Site-Specific		A scenario developed, using site information, either from scratch or by modifying a generic scenario that is consistent with activities in and around the disposal site at the time of closure.
	Reasonably Foreseeable		Reasonably foreseeable scenarios are based on normal activities or other pursuits that are consistent with activities in and around the disposal site at the time of closure. Normal activities include agriculture, dwelling construction, resource exploration or exploitation (e.g., well drilling). The NRC staff continues to believe the generic receptor scenarios associated with normal activities are typically plausible assuming the loss of institutional controls and the loss or significant degradation of the capabilities of intruder barriers. The NRC staff also continues to view the generic receptor scenarios as reasonably bounding over long timeframes, given the uncertainty in estimating future human activities over long time periods. However, licensees can also rely on site-specific scenarios that are consistent with activities in and around the site at the time of closure to limit speculation about future human activity.
	Less Likely but Plausible	Not analyzed for compliance, but may be used to risk-inform the decision.	Intruder activities that are plausible, assuming the loss of institutional controls, based on the capabilities of intruder barriers, site characteristics, and historical uses, but are **not** reasonably foreseeable considering normal activities or other pursuits that are different than activities in and around the site at the time of closure. These scenarios are usually site-specific.
Implausible		No analysis required.	Assuming the loss of institutional controls, intruder activities that could not occur because of persistent physical limitations of the site.

4.3.1.1 *Generic Intruder Receptor Scenarios*

The NRC used a limited number of generic scenarios to inform the development of the 10 CFR Part 61 waste classification criteria (NRC, 1981a, 1982b, 1986a). The receptor scenarios involve both direct and indirect contact with disposed waste through consumption of contaminated food as well as receptor scenarios involving a single, acute exposure and scenarios involving long-term, chronic exposure. The NRC used the direct contact receptor scenarios to develop the 10 CFR Part 61 waste classification and segregation criteria (NRC, 1981a, 1982b) and later, to update the analysis (NRC, 1986a). The receptor scenarios selected were hypothetical constructs intended to provide reasonable bounds on the exposure of inadvertent intruders to radiation from the LLW; these receptor scenarios helped establish waste classification criteria to be applied at all licensed disposal sites. Loss of institutional control is not expected, but the long-term integrity of the controls cannot be ensured, as the control is primarily derived from records, markers, and government processes and actions, all of which may not be durable over many generations.

Three direct contact receptor scenarios involve acute exposures, one direct-contact receptor scenario involves chronic exposures, and one groundwater receptor scenario involves chronic exposures as discussed below:

(1) <u>intruder-construction</u>, in which the intruder receives acute exposures while excavating into disposed waste during construction of a dwelling or building

(2) <u>intruder-discovery</u>, a variant of the intruder-construction scenario, in which the intruder recognizes the presence of waste during excavation and ceases activity

(3) <u>intruder-drilling</u>, in which the intruder receives an acute exposure while drilling through the waste to install a well

(4) <u>intruder-agriculture</u>, in which an intruder receives chronic exposures following construction of a dwelling built in the intruder-construction scenario

(5) <u>intruder-well</u>, in which an intruder is chronically exposed to contaminated groundwater while living on the disposal facility site

Table 4-2 summarizes these scenarios and the pathways by which the intruder received exposures. The following subsections discuss the details of the receptor scenarios themselves.

4.3.1.1.1 Intruder-Construction and Intruder-Discovery Receptor Scenarios

The intruder-construction receptor scenario involves the construction of a dwelling directly above the disposed waste. During construction activities, workers are assumed to come in contact with some of the waste (e.g., during excavation of a basement). Some of the waste is also assumed to be dispersed into the air by the excavation and emplaced onto the immediate area around the dwelling's foundation. Exposures are estimated for pathways listed in Table 4-2, including inhalation of contaminated dust, exposure to direct gamma radiation from standing on contaminated soil and being immersed in a contaminated dust cloud, and ingestion of contaminated dust or food on which contaminated dust has deposited.

Table 4-2 Exposure Pathways of Generic Intruder Receptor Scenarios

Receptor Scenario	**Exposure Pathway**							
	Inhalation#		Ingestion†			Direct/External‡		
	Air	Soil	Food (Air)	Food (Soil)	Food (Water)	Air	Soil Surface	Soil Volume
Acute Exposures								
Intruder-Construction	•		•			•		•
Intruder-Discovery	•		•			•		•
Intruder-Drilling	•		•			•		•
Chronic Exposures								
Intruder-Agriculture	•		•	•		•		•
Intruder-Well		•			•	•	•	

Inhalation includes pathways originating via breathing contaminated air due to suspension of soil particles caused by human activity (air) and caused by natural suspension and volatilization of surface soil (soil).

† Ingestion includes pathways for plant-to-human, plant-to-animal-to-human, and plant-to-animal-to-product-to-human uptake. Food (air) considers food pathways originating via atmospheric deposition on plant surfaces and surrounding soil leading to soil-to-root transfer. Food (soil) considers food pathways originating via soil-to-root transfer from contaminated soil. Food (water) considers food pathways originating via irrigation deposition on plant surfaces and the surrounding soil as well as uptake of radionuclides originating from ingestion of contaminated water (i.e., water-to-human; water-to-animal-to-human; and water-to-animal-to-product-to-human).

‡ Direct/External includes exposure to gamma rays from standing in homogeneously contaminated air (air), standing on a homogeneously contaminated surface area (surface), and standing on homogeneously contaminated ground (volume).

Since this receptor scenario is limited to construction activities, release and subsequent exposure occur for a limited period of time sufficient to complete construction activities for a typical dwelling (i.e., less than a year). The length of time that the intruder is exposed to radioactivity is a function of the stability of the waste encountered. If the waste is assumed to be degraded into an unrecognizable form, then it is possible that such construction activities could proceed following intrusion into the waste. However, if the waste is stabilized to the point that the waste is clearly distinguishable as something different than natural materials (e.g., soil), then it is likely that the inadvertent intruder would stop and investigate. In this case, a subset of the intruder-construction scenario is envisioned and is termed the intruder-discovery scenario. The exposures in the intruder-discovery scenario are expected to occur over a very limited period of time (i.e., less than a day) since it is considered unlikely that construction would resume following the discovery.

4.3.1.1.2 Intruder-Drilling Receptor Scenario

The intruder-drilling receptor scenario is a variant of the intruder-construction scenario that was developed in an update to the initial impacts analysis (NRC, 1986a). The intruder-drilling scenario assumes that, in order to build the dwelling, as in the intruder-construction scenario, the intruder must first install a well to secure an adequate water supply for living needs. During drilling activities, the drilling crew is assumed to inadvertently drill through the waste, bringing it up to the surface in the drill cuttings. If resistance is encountered (e.g., from resistant intruder barriers) during drilling, the crew is assumed to simply move a few yards horizontally to a new location and drill a second borehole. Exposures are estimated for pathways listed in Table 4-2 and include exposure to direct gamma radiation from standing in the vicinity of the borehole, where drill cuttings collect, or a mud pit if drilling fluids are used. Because this receptor scenario is limited to drilling activities, release and subsequent exposure occur for a very limited period of time sufficient to complete drilling activities (i.e., typically less than a day). Though a mud pit was evaluated in the initial analysis, current practices vary (e.g., drill cuttings are sometimes spread on the surface). The licensee should justify the assumed cuttings management practices.

Exposures are estimated for pathways similar to those evaluated in the intruder-construction scenario and are listed in Table 4-2. The exposure pathways include inhalation of contaminated dust from drilling, exposure to direct gamma radiation from standing in the vicinity of the contaminated drill cuttings, being immersed in a contaminated dust cloud, and ingestion of contaminated dust or food on which contaminated dust is deposited. The primary difference between this receptor scenario and the intruder-construction scenario, other than exposure time, is the volume of waste exhumed. The receptor scenario assumes that drilling is performed to supply water for living needs for a single dwelling. The volume of material exhumed is limited to the dimensions of the borehole rather than the dimensions of the dwelling footprint.

4.3.1.1.3 Intruder-Agriculture and Intruder-Well Receptor Scenarios

The intruder-agriculture receptor scenario involves an individual or individuals living in the dwelling constructed in the intruder-construction scenario. Exposure pathways for the intruder-agriculture scenario, given in Table 4-2, include those considered for the intruder-construction scenario in addition to consumption of (1) food grown in the contaminated soil, (2) animals that consumed contaminated fodder, and (3) contaminated animal products (e.g., milk and eggs).

The intruder-agriculture scenario is assumed to be possible only if the waste has been degraded to a form that is indistinguishable from soil. The length of time that the individuals would spend in the contaminated area would be greater for this receptor scenario than for the former intruder-construction scenario because the former scenario is only concerned with exposures to the intruder during construction activities.

The intruder-agriculture scenario used in the waste classification tables did not include consumption of water from an onsite well (as in the intruder-well scenario) because the exposures from migration of radionuclides in groundwater are much more a function of site-specific environmental and geohydrological conditions and total activity rather than directly related to waste concentration. NUREG-0782 (NRC, 1981a) recommends that radionuclides that are important from a migration standpoint have inventory limits established on a site-specific basis, based upon groundwater migration considerations. Licensees evaluating the generic intruder-agriculture scenario should also consider the use of contaminated groundwater from an onsite well in the intruder assessment to demonstrate compliance with Section 61.42. Incorporating the intruder-well scenario into the intruder-agriculture scenario, ensures that licensees consider the consumption of food grown in contaminated soil as well as consumption of contaminated well water and exposure to ground and plant surfaces that are irrigated from the intruder well.

4.3.1.1.4 Criteria for Selecting Generic Receptor Scenarios

Licensees may adopt the generic receptor scenarios described in Section 4.3.1.1 to demonstrate compliance if the facility's design, operation, and site are suitable for their use. The scenario used to demonstrate compliance with the performance objective should consider the greatest reasonably foreseeable dose to the inadvertent intruder. Because of the reasonably conservative nature of the generic-receptor-scenarios approach, the estimated radiological exposures are anticipated to be greater than estimates using site-specific receptor scenarios because the generic receptor scenarios usually contain a nearly comprehensive number of exposure pathways. Use of the generic receptor scenarios may save licensees time and effort by reducing the amount of site characterization, modeling analysis, and reviews needed compared to using a site-specific receptor scenario.

Licensees should be aware that use of the generic receptor scenarios may not be appropriate to demonstrate compliance for certain sites because of the following factors that may limit or alter the activities and exposure pathways for an inadvertent intruder:

- characteristics of the disposal site, such as the presence of adequate water
- facility design, particularly the expected long-term capabilities of engineered intruder barriers
- disposal practices, such as waste emplacement as a deterrent to intrusion
- waste characteristics, including migration behaviors of radionuclides and progeny

Licensees should demonstrate that the use of a generic receptor scenario is reasonable at a particular site and for the facility design and disposal practices. Section 4.3.1.2.1 contains guidance on using site-specific physical information to justify the scenario(s) used to demonstrate that the inadvertent intruder performance objective is met. Examples 4.2 through

4.5 provide examples that should be considered by licensees in selecting a generic receptor scenario to demonstrate the inadvertent intruder performance objective is met. Depending on the characteristics of the disposal facility and its environment, licensees may need to or elect to consider other site-specific receptor scenarios (e.g., industrial, urban, or recreational) or consider additional exposure pathways (e.g., radon gas migration) to modify the generic receptor scenarios.

Reviewers should assess a licensee's analysis of whether the generic receptor scenarios are suitable representations of actual site conditions and disposal practices (e.g., the spatial distribution of radionuclides). The reviewer should consult information provided to demonstrate compliance with 10 CFR 61.12 to support the evaluation. NUREG-1199, Revision 2, "Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility," issued January 1991 (NRC, 1991a), provides guidance on information licensees should submit to demonstrate compliance with 10 CFR 61.12.

NUREG-1200, Revision 3 (NRC, 1994), provides guidance for reviewers to evaluate the sufficiency of the information submitted to demonstrate compliance with 10 CFR 61.12. In general, the generic receptor scenarios are acceptable for demonstrating compliance if licensees can demonstrate that the scenarios are suitable for the disposal facility and would reasonably be expected to result in greater exposure to radiation from the waste than other reasonably foreseeable receptor scenarios. The reviewer's evaluation should also assess the licensee's justification for the evolution of site conditions over the time periods of interest (i.e., compliance period, protective assurance period, or performance period) and over what time the conditions that may have supported the licensee's determination persist. For instance, if a license applicant, in proposing a new facility, were to rely on a receptor scenario that is consistent with activities that are anticipated around the site at closure, which could be many

Example 4.2

A licensee proposes to dispose of all waste 10 meters below the ground surface. The licensee performs an intruder assessment to demonstrate compliance with 10 CFR 61.42 using the generic intruder-construction (acute) and intruder-agriculture (chronic) receptor scenarios.

Conclusion: The generic intruder receptor scenarios identified above may not be suitable to demonstrate compliance because they reasonably assume residential construction that typically does not occur deeper than approximately 3 meters. Therefore, these scenarios do not directly contact the disposed waste. To justify the suitability of the default scenarios, the licensee may evaluate other reasonably foreseeable generic (e.g., intruder-driller, intruder-well) or site-specific scenarios in which the intruder contacts the waste to demonstrate that the selected scenarios would reasonably be expected to result in the greatest exposure to radiation from the waste rather than reasonable alternatives. Alternatively, the licensee may justify why other plausible scenarios are not reasonably foreseeable. The licensee should consult Section 4.3.1.2 for guidance on screening scenarios based on site-specific information.

Example 4.3

A disposal facility is located in a geographic region that currently lacks of an adequate ground water source for purposes of drinking and irrigation. The licensee demonstrates that the inadvertent intruder performance objective is met using the intruder-agriculture receptor scenario but excludes the exposure pathways resulting from the intruder-well receptor scenario.

Conclusion: Excluding exposure pathways from the intruder-well receptor scenario may be appropriate for this disposal facility given the site conditions. The licensee should provide a justification to support exclusion of ground water dependent exposure pathways. The licensee should also demonstrate the expected persistence of those conditions during the operational lifetime of the facility. For a more robust assessment, licensees could also evaluate the impacts of reasonable changes to the current conditions based on future climate conditions during the post-closure time period being evaluated. For example, evolution of the climate in the vicinity of the site may result in greater ground water recharge and lead to an adequate ground water source at some time in the future. Section 4.3.1.2 provides guidance on using site-specific information to screen exposure pathways.

decades away, the applicant should provide a basis to support future site conditions at the time of closure. Likewise, a licensee proposing to eliminate certain pathways from a receptor scenario due to the persistence of an engineered barrier should provide a technical basis that supports the persistence of the engineered barrier to preclude the eliminated pathway(s).

Example 4.4

A licensee proposes an engineered facility in which all waste is disposed of in reinforced concrete trenches (e.g., hot waste cell). The licensee performs an intruder assessment to demonstrate that the 10 CFR 61.42 performance objective is met using the default intruder-discovery receptor scenario.

Conclusion: The default intruder-discovery receptor scenario may be suitable to demonstrate that the performance objective is met during the time period when the hot waste cell would be distinguishable from the native rocks and sediments that an intruder might encounter at the site. The licensee should provide a technical basis, including a consideration of cementitious degradation processes and consideration of local geology, to support the time period over which the hot waste cell would be distinguishable from native rocks and sediments. The licensee should consult Section 4.3.1.2 for guidance on screening scenarios based on site-specific information. The licensee should also demonstrate either that other site-specific scenarios are not reasonably foreseeable, or that the intruder-discovery scenario results in a greater radiological exposure than other reasonably foreseeable site-specific scenarios.

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Example 4.5

A licensee proposes to dispose of large quantities of depleted uranium at a disposal facility. The licensee demonstrates that the inadvertent intruder performance objective is met using the generic receptor scenario with the default exposure pathways that result in the greatest radiological exposure to the intruder.

Conclusion: In this example, the licensee should consider information regarding site-specific waste characteristics in developing a scenario to demonstrate the performance objective is met. The scenario should include credible exposure pathways. The generic scenarios do not assess exposure to radon gas, a decay product in the uranium-238 decay chain, which can migrate from the disposal cell to the surface of the site. The licensee should evaluate potential impacts from radon generation, migration to the surface, and potential exposures to an intruder for comparison with the performance objective. If necessary, the licensee may need to consider additional disposal requirements, such as minimum disposal depths or engineered intruder barriers, to provide assurance that an inadvertent intruder is protected.

Because of the uncertainties in projecting human behavior far into the future, there may be limitless speculation on the types of activities an intruder may engage in, many possibly unknown at this time. The activities represented by the generic receptor scenarios are considered normal human activities (e.g., providing shelter, engaging in agriculture, and seeking natural resources such as water) and avoid excessive speculation about future human activities. The generic receptor scenarios also can be used to evaluate a nearly comprehensive set of exposure pathways and are expected to be sufficient to assess the need for additional measures to mitigate doses to inadvertent intruders. Licensees can use information on the likelihood of natural processes to support receptor scenario development over the longer term.

For example, licensees can assess the effects of potential degradation of the capabilities of intruder barriers (e.g., concrete degradation or erosion of cover materials) to justify when one of the generic receptor scenarios can be initiated. However, speculating on future human disruptive activities beyond a few hundred years should be avoided because there is no scientifically credible basis to estimate the likelihood of a human disruptive activity so far into the future. Reviewers should evaluate the licensee's scenario(s) for demonstrating the inadvertent intruder performance objective is met for consistency with the types of activities associated with the generic receptor scenarios described in this section or with the types of activities expected in and around the disposal site at the time of closure for site-specific scenarios, which are discussed in more detail in Section 4.3.1.2. Reviewers should also evaluate the technical basis supporting the long-lived capabilities of intruder barriers and long-term evolution of the site environmental conditions that may affect receptor scenarios. For example, a licensee should appropriately consider long-term degradation processes such as corrosion or cement degradation in evaluating the longevity of intruder barrier capabilities. Section 4.2.2 discusses guidance for evaluating the longevity of intruder barrier capabilities. Section 2.2.3 discusses considerations in evaluating whether a licensee has provided adequate model support to provide confidence in the projection of long-term processes. Section 5.0 presents guidance on long-term site stability (e.g., erosion).

4.3.1.2 *Site-Specific Intruder Receptor Scenarios*

Site-specific receptor scenarios, which are developed by the licensee, give licensees greater flexibility in developing the scenario(s) to demonstrate that the inadvertent intruder performance objective is met. In developing a site-specific receptor scenario or modifying a generic receptor scenario using site-specific information, licensees should provide a technical basis to support the scenario. The receptor scenario(s) used to demonstrate that the performance objective is met should be a reasonably foreseeable receptor scenario or scenarios that result in estimates of exposure to the inadvertent intruder that tend to not underestimate potential exposures; other reasonably foreseeable receptor scenarios should not result in higher doses to an inadvertent intruder than the scenario(s) selected to demonstrate that the performance objective is met. This does not mean that the scenario with the highest estimated exposure should be selected, but rather of the *reasonably foreseeable* receptor scenarios, the scenario that results in the highest exposure should be selected to demonstrate that the performance objective is met. As described in Table 4-1, reasonably foreseeable receptor scenarios may consider the capabilities of intruder barriers, site characteristics, likelihood of contacting certain waste, and trends and area land use plans. Licensees may consider intruder activities typical of the generic scenarios that are plausible within the specific time period being evaluated (i.e., compliance period, protective assurance period, or performance period) assuming the loss of institutional controls and considering the capabilities of intruder barriers and the natural evolution of site characteristics are acceptable to develop reasonably foreseeable receptor scenarios. Use of generic scenarios limits excessive speculation about future human activity. Licensees may also consider intruder activities that are site-specific and consistent with activities anticipated in and around the site at the time of facility closure to develop reasonably foreseeable receptor scenarios.

The types of site-specific information that a licensee should use to justify selection of a receptor scenario to demonstrate the inadvertent intruder performance objective is met are broadly categorized as physical information and cultural information. Physical information includes the location, climate, topography, geology, soil types, and water availability of the site, including features of the disposal facility such as waste characteristics, disposal methods, and the use of intruder barriers. Cultural information is essentially how the human population uses the land. Physical properties of the site may change over time, particularly long time periods; however, the change is expected to be slow compared to changes in the cultural use of the land. Because of the uncertainty in estimating future human disruptive activities, cultural use of the land is anticipated to be very uncertain over long time periods. Therefore, licensees should not rely on cultural information as a basis for receptor scenario selection beyond a few hundred years. Rather, licensees should limit consideration of cultural information to the operating lifetime of the disposal facility.

The level of justification and analysis that should be provided by the licensee will depend on the reasonableness of the physical characteristics the potentially foreseeable land uses, and the length of time that the radiological hazard persists at the site. Licensees modifying generic receptor scenarios or developing a site-specific intruder receptor scenario should consider the performance of intruder barriers and the evolution of site characteristics over the duration of the radiological hazard. Conversely, licensees modifying generic receptor scenarios or developing site-specific intruder receptor scenarios should limit consideration of potential future uses of the site and demographic information to the time of facility closure. Such considerations might include characteristics of the disposed waste, disposal practices, degradation processes of intruder barriers, estimates of the evolution of site characteristics, and, when appropriate, the prevailing and possible future uses of the land, within the operational lifetime of the facility, that could constrain use. Several potential intruder receptor scenarios may need to be evaluated to determine the reasonably foreseeable receptor scenario resulting in the greatest exposure. These scenarios could be based on different combinations of site-specific receptor scenarios developed from radiological characteristics, disposal practices, evolution of physical characteristics of the site, and expected land use.

Selection of site-specific receptor scenarios or the modification of generic exposure pathways will typically require a technical basis that accounts for the longevity of the hazard. Licensees should base justifications for modifying generic receptor pathways or developing unique site-specific receptor scenarios on: (1) waste characteristics and disposal practices; (2) the nature of the land and reasonable estimates based on physical and geologic characteristics; and (3) societal uses of land based on past historical information, current uses, and what is reasonably foreseeable in the near future (i.e., at the time of facility closure). The reviewer should evaluate the justifications provided by the licensee for the selection of the receptor scenario(s) used to demonstrate the inadvertent intruder performance objective and the screening of alternate plausible receptor scenarios considering the following guidance related to the use of site-specific information.

4.3.1.2.1 Site-Specific Physical Information

Physical information about the site includes information related to waste characteristics and disposal practices as well as site physical characteristics. Site-specific physical information can be used as a basis to modify the generic receptor scenarios and associated pathways. The physical information should focus on key factors that would impact the likelihood of an intruder who is engaging in normal activities (e.g., agriculture, dwelling construction, or other pursuits such as resource exploration) or other reasonably foreseeable pursuits that are consistent with activities in and around the site at the time of closure in which the person might be unknowingly exposed to radiation from the waste.

4.3.1.2.1.1 Waste Characteristics and Disposal Practices

Licensees may consider both waste characteristics and disposal practices when developing an appropriate receptor scenario to demonstrate the performance objective is met. This site-specific information can affect the level of information needed to support the use of other physical or cultural information. For example, the hazard from long-lived waste would require a consideration of the evolution of site characteristics, such as climate, for a longer period than for shorter-lived waste. Reviewers should consider the effects of this information on selection of an appropriate receptor scenario.

A key waste characteristic is the longevity of the hazard from the disposed waste. The longevity of the hazard should be considered as a factor when using other site-specific information to develop receptor scenarios. For example, if a facility accepts only shorter-lived waste (e.g., waste containing only radionuclides with half-lives on the order of the radionuclides listed in Table 2 in 10 CFR 61.55), then the consideration of the potential evolution of the physical characteristics of the site can be limited to a shorter time period commensurate with the time it takes for the shorter-lived waste to decay and result in an acceptable exposure to the inadvertent intruder. For long-lived waste, consideration of land use information to justify the selection of less conservative receptor scenarios may not be appropriate given the uncertainty in estimating future human behavior. The use of land use information is discussed further in Section 4.3.1.2.2 below.

Another important consideration is the use of disposal practices such as the presence of intruder barriers (e.g., a wasteform designed to be recognizable for long time periods or the depth of waste emplacement intended to limit direct contact with the waste). Intruder barriers that are expected to be recognizable over a given timeframe may prevent inadvertent intrusion or limit potential receptor scenarios over that time period. Licensees should provide an adequate technical basis for the time period over which a barrier's capabilities would limit direct contact with the waste or limit an inadvertent intruder's radiological exposure. Licensees are expected to provide a technical basis to support the use of intruder barriers that are expected to be effective for more than a few hundred years. The analysis should evaluate whether the barrier precludes or mitigates intruder exposures. The technical basis should also consider the evolution of the physical conditions to which the intruder barriers would be exposed over the duration of the hazard.

For example, a licensee may rely on depth of disposal to limit the consideration of an intruder-construction type of receptor scenario (see Example 4.6). In this example, the licensee's technical basis for exclusion of an intruder-construction scenario should include an assessment of the effects of erosion and other geomorphologic processes at the site to understand whether the depth will be sufficient over the duration of the hazard of the disposed waste. Reviewers should evaluate the adequacy of the technical basis for intruder barrier capability using the guidance in Section 4.2.

Example 4.6

A licensee proposes a new disposal cell in which long-lived waste is emplaced beneath an intruder barrier at least 5 meters thick. The licensee eliminates from further consideration the default scenarios based on the thickness of the cover, and proposes an alternate site-specific scenario.

Conclusion: While the alternate site-specific scenario may be appropriate given the cover depth, reviewers should confirm that the screening of the default scenarios due to the presence of the cover is justified over the portion of the time period analyzed that the long-lived hazard persists. The reviewers should confirm that the licensee has adequately evaluated the longevity of the cover (e.g., the cover thickness), and the cover's ability to limit contact with the waste by the default excavation scenario over the duration of the long-lived hazard. The evaluation should consider geomorphologic processes (e.g., erosion) including the impact of any long-term evolution of the site characteristics (e.g., climate) on the rate of geomorphism at the site. If the licensee cannot adequately demonstrate that the cover will remain thick enough to limit contact with the waste when considering long-term evolution of intruder barrier capabilities, then the default scenarios should be evaluated to determine if the scenarios result in a greater exposure to radiation from the waste compared to the licensee's alternate scenario. The licensee should consult Section 4.3.1.2 for guidance on screening scenarios based on site-specific information.

4.3.1.2.1.2 Characteristics of the Disposal Site

Licensees may consider the physical characteristics of their disposal site (e.g., the presence of natural resources such as water and its quality and quantity, soil conditions, topography, and climate) in justifying an appropriate receptor scenario to demonstrate the inadvertent intruder performance objective is met. The consideration of physical characteristics often results in modifications of receptor scenarios rather than complete elimination of the scenario type. For example, farming may not be supported because of poor soil quality (i.e., not economically practical), but residential gardening may still be reasonable. The justification should also include an assessment of the physical characteristics over the period of time a significant hazard from the disposed waste persists (see Example 4.7). Reviewers should evaluate the justification for modifying generic receptor scenarios or selecting site-specific receptor scenarios based on a site's physical characteristics.

Example 4.7

A licensee proposes a site-specific residential scenario that excludes water pathways because of a current lack of water suitable for drinking or irrigation at the site.

Conclusion: While the alternate site-specific scenario may be appropriate given the current lack of potable water at the site, reviewers should confirm that the screening of the water pathways is justified over the portion of the compliance period that a significant hazard persists. The reviewers should confirm that the licensee has adequately evaluated the natural evolution of the climate over the compliance period. The reviewer should also confirm that the expected evolution of the climate does not result in a change in the potability of the water sources available at the site or their availability for use in irrigation. The evaluation should consider potential changes in precipitation, evaporation, vegetative cover and its impact on transpiration, and their effect on recharge and potability or availability for irrigation at the site. If the licensee cannot adequately demonstrate that the water remains nonpotable over the duration of the compliance period, then the water pathways should be included in the scenario.

Reviewers should also confirm that the screening of the water pathways is justified over the portion of the protective assurance period that a significant hazard persists. Because the potability of water from the aquifer may be affected by dynamic climatic changes which are not expected to be static during the compliance period, licensees would need to provide a justification that the continuing evolution of the climate would not lead to a potable water source during the protective assurance period. Licensees may be able to simply estimate the change in the level of chemical constituents that cause the non-potability based on future expected climates and demonstrate that the potability of the water would not change based on the estimates of future constituent levels. For instance, a licensee may need to demonstrate that under wetter future climates, increased infiltration would not decrease the total dissolved solids of a non-potable aquifer sufficiently to change the water source's potability during the protective assurance period according to drinking water standards in effect today.

The existence of natural resources may result in reasonably foreseeable exploratory activities at the site, though it should be noted that 10 CFR 61.50(a)(4) requires that areas that have known natural resources that, if exploited, would result in failure to meet the performance objectives of

10 CFR Part 61, Subpart C must be avoided during siting. Because of the uncertainty in estimating future human activity, licensees do not need to speculate on a future society's interest in known resources that are not economically viable in the vicinity of the site after closure. When reviewing the technical basis involving the presence or absence of economically viable resources at the site, reviewers should limit speculation about natural resources that may be economically viable to future societies after closure. Rather, reviewers should focus on natural resources for which exploration is currently being conducted in the region of the site (i.e., within an 80-kilometer (50-mile) radius of the site). Natural resources not currently being extracted in the region of the site may still be considered if their presence is currently known to exist in economically viable quantities in the immediate vicinity of the site.

Justification to limit receptor scenarios and exposure pathways for intruders based on groundwater quality and quantity should be based on site conditions rather than local codes and should be based on classification systems used by the EPA or the State, as appropriate. Arguments involving depth to water table or well production capacity should have supporting documentation from either the U.S. Geological Survey (USGS), an appropriate State agency, or an independent consultant. Tables M.5-M.12 in NUREG-1757, Appendix M (NRC, 2006) provides additional details on water quality standards.

Licensees using soil quality as a justification for modifying receptor scenarios should provide supporting documentation from the U.S. Natural Resources Conservation Service, appropriate State or local agency, or an independent consultant. Reviewers should carefully consider whether the state of the soil would reasonably preclude all activities or only certain activities. In most cases, soil quality can reasonably preclude activities such as crop production, but could allow grazing or small gardens.

Licensees using topography as a justification for modifying receptor scenarios should provide supporting documentation of the existing topography in the form of pictures, USGS or similar topographic maps, hand-drawn maps, or a detailed description of how the topography would limit activities. Licensees may need to conduct landform evolution modeling that might also include expert elicitation to provide support for reasonably foreseeable landform changes to local topography. See Section 5.0 for additional guidance for long-term landform evolution.

When reviewing justifications involving topography, the reviewer should limit speculation about future topographical changes from offsite civil engineering projects, but not topographical changes from the final closure design of the disposal facility itself. The reviewer should evaluate the reasonableness of the inadvertent intruder performing activities on the current topography; for example, a slope, and reasonable evolution of the site due to geomorphologic processes (e.g., fluvial, eolian, tectonic, biological). Reviewers may wish to perform a site visit to evaluate the current topography first hand and assess how the disposal design may impact the current topography. For example, reviewers may wish to assess the effect of runoff from a licensee's cover system on erosion of the site topography.

4.3.1.2.2 Site-Specific Cultural Information

Licensees may consider cultural information in justifying an appropriate receptor scenario or scenarios to demonstrate the performance objective is met. Cultural information is essentially how land is used by the human population and describes the types of normal activities an inadvertent intruder might engage in on the site. Information on land use can be based on past, current, or projected land uses. The shorter of either the anticipated operational lifetime or one hundred years is a reasonable period of interest for future land use projections to provide the basis for receptor scenarios, depending on the rate of change in the region, and the peak exposure time. Note that the 100-year timeframe described here is only for estimating future land uses to justify a receptor scenario; the licensee must evaluate doses that could occur over the time periods specified in the regulations. However, because of the uncertainty in estimating future human behavior, cultural information projected beyond the operational lifetime of the disposal facility should not typically be used as justification for a receptor scenario. Instead licensees may rely on suitable physical information and should refer to Section 4.3.1.2.1 for guidance on its use in justifying a scenario to demonstrate that the inadvertent intruder performance objective is met.

A licensee's assumptions about land use should focus on current practice in the region of concern, which can be as large as an 80-kilometer (50-mile) radius. To narrow the focus of current land practices, the licensee can use information on how land use has been changing in the region and should give more weight to land use practices either close to the site or in similar physical settings. Licensees should also evaluate land uses that occur in locations outside the region of concern that share characteristics (temperature, precipitation, topography) expected for the region of concern over the duration evaluated in a site-specific receptor scenario. Consideration of environmental-analog regions may help identify whether present-day land uses have been driven by past socio-economic development. Land uses primarily resulting from socio-economic development are generally more uncertain over longer time periods than land uses primarily resulting from physical conditions (e.g., climate).

Licensees should categorize potential land use as reasonably foreseeable, less likely but plausible, or implausible. Any land uses that similar real-estate properties in the region currently have, or may have in the near future (e.g., in approximately 100 years or the operational lifetime of the disposal facility) should be characterized as reasonably foreseeable. Consideration should be given to trends and area land use plans in determining the likelihood of potential land use. Land uses that are plausible, generally because similar land either was used for this purpose historically in the region of interest, or is used currently in regions with analogous environmental characteristics, but that are counter to current trends or regional experience should be characterized as less likely but plausible. Licensees should provide either a quantitative analysis or qualitative argument discounting the need to analyze all scenarios generated from the less likely but plausible land uses. If peak doses from the less likely but plausible land uses are significant, the licensee should provide greater support that the receptor scenario is unlikely to occur. Implausible land uses are those that, because of physical limitations, could not occur. Because of the uncertainty in predicting human behavior in the future, land use information should be consistent with normal activities or other activities that typically occur in and around the site at the time of closure of the disposal facility.

Reviewers should evaluate the justification provided for the selection of reasonably foreseeable scenarios. One goal of the review is to ensure that, if land uses other than the reasonably foreseeable land use were to occur in the future, significant exposure would not result. Reviewers may wish to involve State and local land use planning agencies in discussions if the licensee has not already requested their involvement. Additional guidance on potential sources of land use information is available in Appendix M.5 to NUREG-1757 (NRC, 2006).

4.3.2 Model Abstraction

Model abstraction is the process of incorporating the significant FEPs into a conceptual model that can reasonably describe how the facility limits the inadvertent intruder's radiological exposures. As discussed in Section 2.7.2, the conceptual model is then abstracted so that it can be represented in a mathematical model to estimate potential radiological exposure and the associated uncertainties. In this way, model abstraction for an intruder assessment is similar to model abstraction for a performance assessment. Because of the similarity in the model abstraction process for performance assessments and intruder assessments, the guidance in NUREG-1573, Section 3.3 (NRC, 2000a), may also be generally applicable to the intruder assessment. The following sections discuss modeling issues that require additional, specific guidance applicable to the intruder assessment.

The abstraction process for the intruder assessment may be more stylized than for the performance assessment depending on the particular receptor scenario used to demonstrate that the performance objective for protection of the inadvertent intruder is met. Inadvertent intrusion receptor scenarios involving direct contact with the waste are generally expected to use more stylized modeling approaches because the release of radionuclides from the disposal units is primarily affected by the assumed human activities. For example, an intruder assessment evaluating direct contact with the waste may be limited to abstractions for the degradation of intruder barriers, the source term, and the resulting biosphere exposures, while receptor scenarios involving the release and migration of radionuclides through the site environment as a result of natural processes may use modeling approaches that are more similar to performance assessments.

General considerations for performing and reviewing model abstractions of the various technical analyses are discussed in Section 2.0 of this guidance and may apply to an inadvertent intruder assessment. Guidance on selecting site-specific input parameters for the models and providing technical basis can also be found in NUREG-1757, Section I.6 (NRC, 2006). The guidance in NUREG-1757 is oriented toward decommissioning activities; however, the concepts presented are also generally relevant to intruder assessment for LLW disposal.

Reviewers should focus on understanding the importance of various assumptions, models, data, and uncertainty in the intruder assessment. To review the overall intruder assessment, the reviewer should recognize that models used by a licensee may range from highly complex process-level models to simplified models, such as response surfaces or look-up tables. The reviewer should determine whether uncertainties in the models and parameters are appropriately accounted for in the intruder assessment. Section 2.2.2 of this document discusses general considerations for uncertainty and sensitivity analysis.

An intruder assessment can be a collection of models of varying complexity or it can be an integrated model. Intruder assessment commonly involves the execution of numerical models that mathematically represent the conceptual model of the contaminated site. The numerical models used to implement the mathematical equations are usually linked via the conceptual model and codified in a software package known as "the code." Reviewers should ensure that the intruder assessment codes and models and the associated databases are properly documented and verified in accordance with a QA/QC criterion that is acceptable to the NRC staff. Chapter 9 of NUREG-1199 and NUREG-1200 provide guidance on the information needed to comply with the QA requirements specified in 10 CFR 61.12(j) (NRC, 1991a; 1994).

Further, NUREG-1293 (NRC, 1991c) provides specific guidance on how to meet the 10 CFR Part 61 QA requirements. If site-specific models and codes are used, a justification of the conceptual model should be provided. Reviewers should also review the source term models, the transport models, the exposure models, and the overall dose models. Reviewers should assess the QA/QC documentation and the level of conservatism of any alternate code and model. Section I.5 of NUREG-1757 (NRC, 2006) provides guidance, in the context of decommissioning activities, which is generally relevant to intruder assessments on the selection of codes and models and approaches for NRC acceptance of the codes and models. Section 2.7.1.2 of this document provides additional information on quality assurance.

The following sections discuss guidance on developing specific model abstractions for intruder assessment and general model development issues.

4.3.2.1 *Intruder Barriers*

The intent of an intruder barrier is to inhibit contact with waste and help ensure that an inadvertent intruder's radiation exposure will be limited, which provides reasonable assurance that the performance objectives can be met. A variety of intruder barriers may be employed at a waste disposal facility depending on the nature of the waste, the facility design, and the site characteristics. Intruder barriers may include a sufficient depth of cover over the waste or engineered structures that provide protection to the inadvertent intruder (e.g., engineered covers, concrete vaults, engineered wasteforms, or waste containers). Each intruder barrier will have a time period over which it will perform its intended functions, which should be justified by the licensee. Additional guidance on justifying intruder barrier capabilities is available in Section 4.2.

The objective of intruder barrier model abstraction is to establish model representations of the intruder barriers that are reasonably consistent with their intended capabilities and their expected behavior with time. A primary outcome of the intruder barrier model abstraction is an estimate of the time after disposal when intrusion could occur. This output is affected by the particular intruder receptor scenario, the design of the intruder barrier system, and the impact of natural processes on the longevity of the intruder barriers' capabilities. Reviewers should apply the general guidance in Section 2.7.2 when evaluating the abstraction of intruder barriers in the intruder assessment. Reviewers should consider the degree to which the licensee relies on the capabilities of the intruder barriers to demonstrate the performance objective is met. For intruder assessments for which licensees have demonstrated that intruder barriers have a minor impact on protection of the intruder, a simplified review should be sufficient.

The nature of the activities in which an inadvertent intruder might engage will affect the time at which an intruder might unknowingly be exposed to radiation from the waste. Licensees should assess the capability of the intruder barrier system to preclude contact with the waste or limit radiological exposures. For example, construction activities could be limited to the discovery receptor scenario as long as the wasteform remains stable, and is, therefore, expected to be distinguishable from soil. Licensees should provide a technical basis for the ability of the intruder barrier to delay the time of initiation for intruder activities. The level of detail in the technical basis should be commensurate with the delay time afforded by the capabilities of the intruder barrier. Barriers providing substantial delay time would require a more robust technical basis. The technical basis should consider insights gained from scenario analysis and beneficial as well as deleterious natural processes that may affect the capability of the barrier to preclude the intruder activities. Reviewers should focus on those barriers that provide substantial delay time to the onset of intruder activities; activities that otherwise would result in direct contact with the waste or other radiological exposures.

In developing intruder barrier models, the licensee should present information on spatial relationships among the physical components (e.g., the layout and physical dimensions of a vault or cover system) and the physical distribution of various types of materials that are used in the intruder barriers. The intruder assessment should include features of the intruder barriers that are most important to demonstrating the performance objective is met. Licensees should ensure that the models for intruder barriers are integrated with related model abstractions. For example, the conditions and assumptions used in the degradation of intruder barriers should be consistent with those used for other model abstractions (e.g., climate and infiltration).

Reviewers should examine the identified physical components that are important to demonstrating the performance objective is met and evaluate whether their representation in the intruder assessment modeling is consistent with their description, the technical basis supporting their capabilities, and other model abstractions. The review should assess whether the descriptions are adequate to detail the important design features, capabilities, and properties of the barriers (e.g., thickness, porosity, or saturation of a cover layer designed to limit gaseous fluxes to the surface). The modeling of intruder barriers by licensees should reflect the level of quality that is expected to be achieved in the implementation of the design. Reviewers should assess whether the level of quality being proposed can be attained, that it is supported by an acceptable quality assurance program, and that it is adequately represented in the abstraction.

Licensees should evaluate processes that may limit the effectiveness of the intruder barriers. Barriers may degrade from internal processes (e.g., interaction between incompatible materials, interaction with the waste) or external processes (e.g., interaction with biota, erosion, leaching by infiltrating water, and processes such as seismically induced cracking). Analysis of a barrier system should be performed in an integrated manner because of potential synergisms between degradation mechanisms. If the analysis is performed assuming that the degradation mechanisms are independent, the reviewer should evaluate the information to determine whether an adequate basis has been provided for the analysis approach (e.g., assuming that the degradation mechanisms can be evaluated as independent). This may include demonstrating that the degradation analysis was reasonably conservative or that uncertainty was adequately characterized and propagated in the model. Reviewers should also verify that the models for degradation of intruder barriers are consistent with environmental parameters, material properties, and assumptions implemented in the performance assessment.

The intruder assessment should account for relevant materials and conditions that could affect the ability of an inadvertent intruder to contact the waste over time. Licensees should consider interactions of the components and materials of the intruder barriers. Factors that may need to be considered include (1) compatibility among materials that may come into contact with each other, (2) the manner in which construction may affect system behavior (e.g., construction joints, changes in geometry, penetrations), (3) the effect that failure of a design feature or some portion of an intruder barrier would have on the overall ability of the intruder barrier system to limit contact with the waste, and (4) how the degradation of material properties affects barrier performance over time.

Representation of the temporal performance of an intruder barrier may be accomplished by dividing the barrier performance into three phases. The first phase is the service life during which the intruder barrier would effectively inhibit contact with the waste and help ensure that radiation exposures will meet the performance objective. The second phase represents a time of decreasing performance from ongoing processes of degradation. It should also be recognized that, for some barriers, the time between initial non-degraded conditions and completely degraded conditions may be quite short. The third or final phase represents complete degradation. In this third phase, the barrier is no longer able to limit contact with the waste. However, barriers that are designed help ensure that radiation exposures will meet the performance objective, rather than inhibit contact with the waste, may still provide some level of diminished performance (see Example 4.8). It is expected that the service life periods of different barriers may vary significantly because of the inherent diversity and variability of the barrier components. This variability in service life would need to be accounted for in the intruder assessment.

Example 4.8

A licensee proposes a reinforced concrete vault as an intruder barrier for the disposal of depleted uranium. The licensee describes the capabilities of the vault to both inhibit contact with the depleted uranium and limit release of radon gas to the surface over some expected service life.

Conclusion: An appropriate model representation would be to limit an inadvertent intruder's contact with the waste during the service life of the vault, provided that an adequate technical basis for the service life is provided. Reviewers should evaluate the adequacy of the technical basis for the service life. When the service life has ended, the applicant could conservatively assume that the vault would return to constituent sand and gravel aggregates and take no credit for the ability of the degraded vault to either inhibit contact with the waste or limit radon diffusion to the surface. Alternatively, the licensee may choose to still consider the ability of the degraded state to sufficiently reduce diffusion of radon to the surface thereby limiting radon exposures to an inadvertent intruder. In this alternate case, the reviewer should evaluate the licensee's basis for the degraded material, including degraded material properties (e.g., effective diffusivity), to continue delaying radon transport to the surface.

Licensees should provide information to support the model estimates of intruder barrier performance. Section 2.2.3 of this document provides guidance on model support. Model support can include laboratory experiments, field measurements, previous experience with similar systems, process modeling of barrier performance (e.g., detailed models of landform evolution to estimate cover erosion), natural or industrial analogs, independent peer review (NRC, 1988a), or additional sources of relevant information. Reviewers should examine the evidence supporting the modeling to confirm that the information is based on similar environmental parameters, material factors, assumptions, and approximations shown to be appropriately analogous and that the models are not likely to underestimate actual degradation and failure of intruder barriers. Reviewers should also examine the procedures that the licensee used to construct and test its mathematical and numerical models. Section 4.2.1 provides guidance on a risk-informed approach to model support for engineered barrier capabilities.

Licensees should assess the uncertainty in model estimates for the longevity of intruder barrier capabilities. This assessment should also evaluate the sensitivity of the potential inadvertent intruder exposures to uncertainties in the support for the model estimates. Section 2.2.2 of this document discusses guidance on dealing with uncertainty.

4.3.2.2 *Source Term*

The objective of the source term abstraction in an intruder assessment is to estimate the radionuclide concentrations in the environment (i.e., the biosphere) accessible to the inadvertent intruder. The modeling of the source term can be one of the most important determinants of the estimated exposures to an inadvertent intruder. Typically, source term modeling includes the inventory of radionuclides, physical and chemical characteristics, and other properties used to estimate release rates.

For the intruder assessment, radionuclides are primarily expected to enter the accessible environment through inadvertent contact with the waste, though entry may also be possible through the use of contaminated surface water or groundwater on the site, or as a result of gaseous releases from the disposed waste to the atmosphere above the site. In direct contact receptor scenarios, the source term modeling estimates the concentration of radionuclides contacted and exhumed to the biosphere that the inadvertent intruder inhabits. These concentrations are then used as input in the biosphere modeling. In indirect receptor scenarios, the source term modeling typically estimates releases occurring by advective or diffusive mechanisms, although other mechanisms may be possible (e.g., biointrusion, erosion). The release rates from the disposal unit are estimated and used as input for transport modeling.

4.3.2.2.1 Inventory

Assumptions about the characteristics of the radionuclide inventory can have a significant effect on the determination and selection of modeling approaches appropriate for representing the source term. Radionuclide inventories need to be addressed on a facility-specific basis. The anticipated distribution of specific radionuclides in the disposal facility inventory should be estimated by waste class (A, B, and C), waste type, wasteform, waste stream, and waste container type, as appropriate. This information provides a basis for selecting an approach for source term modeling. The necessary level of detail in this information will vary with the modeling approaches under consideration. For example, the source term model for direct contact receptor scenarios in which a discrete volume of waste is exhumed may be more stylized than for other scenarios involving release from the disposal units.

Licensees should provide a description of the radionuclide inventory in the disposal facility. All radionuclides should be described by volume, concentration, and location within the disposal system. The radionuclide inventory should be consistent with the resulting waste acceptance criteria as well as the inventory used in the performance assessment to assess whether the requirements of 10 CFR 61.41 are demonstrated. However, in some cases, licensees may use conservative estimates of inventory in the intruder assessment and more realistic estimates in the performance assessments.

Reviewers should evaluate the methods used to characterize the radionuclide inventory and estimate the concentrations of radionuclides not measured to ensure that uncertainty and variability are appropriately accounted for in the source term model.

Licensees may use a screening approach to determine which radionuclides in the facility inventory need to be considered further in the intruder assessment. Licensees may:

(1) Eliminate radionuclides with half-lives less than 5 years that are not present in significant activity levels and do not have long-lived daughter products.

(2) Perform an intruder dose calculation using the generic receptor scenarios discussed in Section 4.3.1.1 assuming that the intruder inadvertently intrudes into the spatially averaged peak waste concentration and that all intruder barriers are completely ineffective in inhibiting contact with the waste. All radionuclides are assumed to be available for all relevant exposure pathways of each generic receptor scenario. Radionuclides with an estimated peak dose in each of the receptor scenarios that is less than 10 percent of the performance objective can be eliminated from further consideration provided that the sum of their doses is accounted for in demonstrating the performance objective is met. If a radionuclide has an estimated peak dose greater than or equal to 10 percent of the performance objective in any of the generic receptor scenarios, the radionuclide should be retained for the final intruder assessment. Computer models such as RESRAD (Yu et al., 2001) may be useful to conduct this type of screening analysis. To ensure that important radionuclides are not inadvertently screened out of the assessment, it is important to confirm that the dominant pathways (i.e., those contributing most to estimated dose) in the screening calculation are consistent with those in the final intruder assessment.

Reviewers should examine the description of the screening assessment to ensure that the licensee used reasonably conservative parameters and appropriately screened the radionuclides.

For intruder receptor scenarios in which direct contact with the waste occurs, source term modeling can be as simple as distributing a concentration of radionuclides in the biosphere for exposure modeling. For receptor scenarios with indirect releases from the disposal cells, such as through advective-diffusive release mechanisms, licensees may develop source term abstractions similar to those in the performance assessment (see Section 3.1). Licensees may also use estimated concentrations from the performance assessment at an appropriate location and point in time to assess exposures to the inadvertent intruder in the biosphere.

Reviewers should verify that licensees using radionuclide concentrations from the performance assessment have not overestimated releases in the performance assessment to conservatively estimate doses to the general public, resulting in a potential underestimation of radionuclide concentrations in the intruder assessment.

Licensees should also consider the radioactive decay before the time of intrusion or may conservatively assume no decay. In either case, however, licensees should consider the impacts of significant progeny on the intruder. Radioactive decay can result in significant ingrowth of progeny at future times. For example, doses from depleted uranium may increase for more than one million years due to ingrowth of shorter-lived and more highly mobile decay products. Given that the regulations specify that 100 years is the maximum duration over which active institutional controls can be relied upon, radioactive decay is expected to be more important in direct contact receptor scenarios for shorter-lived radionuclides such as cesium-137. Reviewers should verify that radioactive decay is appropriately accounted for in the source-term modeling.

Licensees may also account for the time of waste emplacement. Justification should be provided to support the time of waste emplacement. For example, if a licensee assumes that all waste is emplaced in the final year of operation, minimal justification would be needed. Additional justification would be expected to support earlier times of waste emplacement.

4.3.2.2.2 Radionuclide Concentrations for Direct Contact Scenarios

To develop the source term abstraction, licensees should estimate the concentration of radionuclides in the facility at times after which the direct contact scenarios would be expected to occur. Estimating the time after which a direct contact scenario could occur is related to the assumed institutional control period (see Section 4.4), intruder activities envisioned in the receptor scenario, and the capabilities of intruder barriers to preclude intrusion. Section 4.3.2.1 provides guidance on the capabilities of intruder barriers to preclude intrusion.

Licensees should consider the following elements when generating concentrations of radionuclides for the intruder dose assessment:

- Licensees are permitted to account for dilution of the waste following disposal due to mixing with uncontaminated materials in the disposal cells.
- The amount of mixing should account for methods of waste emplacement such as disposal depth.
- The justification for the amount of mixing may rely on site characteristics.
- The justification may include reasonable assumptions about the intruder activities.

Licensees are permitted to account for dilution of the waste following disposal due to mixing with uncontaminated materials in the disposal cells. Licensees should provide a technical basis for dilution of the waste mixed with uncontaminated materials. Mixing should be consistent with the design of the facility, waste emplacement, site characteristics and assumptions about intruder activities for a given scenario. The design of the facility may incorporate uncontaminated materials within the disposal cells that would tend to reduce radionuclide concentrations found in the waste. Design features may include intruder barriers and stabilization materials such as backfill or grout. For example, waste may be emplaced beneath an engineered cover with uncontaminated backfill material to help maintain the stability of the disposal cells. The uncontaminated cover and backfill would likely reduce radionuclide concentrations found in the waste when mixed during excavation, as considered in an intruder-construction scenario.

The amount of mixing should account for methods of waste emplacement. For example, the intruder-construction scenario typically only excavates a depth necessary to construct a dwelling. Waste and backfill placed beneath this depth should not be considered in the mixing assessment. The justification for the amount of mixing may rely on site characteristics. For example, the thickness of uncontaminated soil between the bottom of the disposal cells and the underlying aquifer or resource may also be considered in estimating dilution for an intruder-driller scenario. To justify mixing based on deeper aquifers or resources, licensees should explain why mixing with the uncontaminated soils between the bottom of the disposal cells and the depth of the deeper aquifers or resources would be more appropriate than a smaller mixing volume associated with shallower aquifers or resources. Licensees should limit this mixing volume to the shallowest aquifer or resource that would be reasonable to access for water or the natural resource. Licensees should also consider the impact of variability in the mixing volume associated with the use of shallower aquifers or resources if it is plausible that an inadvertent intruder might access the shallower aquifer or resources.

In the absence of knowledge that the site is a disposal facility, it may be considered reasonable to assume that an intruder will excavate at random locations. In this case, the excavation could exhume material that was contained within multiple waste packages or disposal cells. Therefore, the waste concentration for estimating intruder impacts from excavation can be averaged over the area of the site where waste is disposed, including uncontaminated regions within the disposal cells (e.g., backfill). Portions of the site beyond the disposal cell footprints, such as administrative areas or the buffer zone, should not be included in the areal-average of the waste concentrations. If the excavation area is larger than the disposal cell area, dilution with uncontaminated soil surrounding the disposal cell may be considered.

For intruder-driller scenarios, the waste concentrations may be based on the average concentration in the waste containers (for containerized waste) or the average concentration of the waste for bulk waste. Uncontaminated material above and below the waste may be credited in the intruder-driller waste concentration calculations. However, uncontaminated material within the disposal cell (e.g., backfill) should not be credited because the intruder driller disturbs a small, discrete area. Operational limits, such as waste emplacement strategies, may be necessary to limit the impact from wastes with significant heterogeneity that is near class limits.

Licensees should provide a basis to justify the suitability of the random access assumption. For example, at an aboveground disposal facility characterized by mounded disposal cells that create a “ridge and valley” topography in which the disposal mounds are expansive with gentle terrain and are separated by steep and narrow “valleys” that are uncontaminated, licensees can argue that the excavation of a dwelling foundation would preferentially occur on the expansive “ridges” rather than in the steeper, narrower “valleys”. In this case, random access may not be an appropriate assumption for an intruder-construction scenario.

Reviewers should evaluate the reasonableness of the technical basis supporting the dilution of waste concentrations. The review should consider the facility design, waste emplacement, site characteristics, and scenario assumptions. Generally, the more mixing that is assumed, the more robust the technical basis should be to support the dilution factor.

Radionuclides that are released offsite through natural processes before intrusion are generally not available to be exhumed by an inadvertent intruder. Licensees may consider radionuclide migration before the commencement of the intruder activities. Licensees may use information from the performance assessment to estimate radionuclide releases. However, licensees should exercise caution with this approach if the performance assessment overestimates releases to conservatively assess exposures to the general public. This may result in an underestimation of waste concentrations remaining for the intruder to access.

Reviewers should assess the consistency between radionuclide releases estimated in the intruder assessment and in the performance assessment. Reviewers should ensure that pessimistic modeling biases and assumptions in the performance assessment do not result in overly optimistic biases in the intruder assessment.

The spatial extent over which exhumed waste is deposited at the surface on site will depend on the activities assumed to occur in the intrusion receptor scenario (e.g., drill cuttings management practices) and physical arguments about the exhumed volumes (i.e., how widely can a volume of exhumed waste physically be spread?). The area over which exhumed material is spread may be an important parameter because it can limit certain exposure pathways. For example, too small an area may make certain agricultural pathways unviable, while too large an area may unreasonably dilute the concentration of the waste exhumed. For the spatial distribution of the exhumed radionuclides, licensees should use reasonable physical assumptions consistent with the scenario assumptions. For example, a small volume of drill cuttings is not likely to be spread over a large area of the site.

Reviewers should evaluate the licensee's basis for the extent of contaminated material in the biosphere. Reviewers should assess the consistency between the assumptions about spatial distribution of exhumed radionuclides and the assumed activities of the receptor scenario.

4.3.2.2.3 Radionuclide Concentrations for Transport Scenarios

Reviewers should assess the adequacy of the radionuclide release and transport models in the intruder assessment consistent with the guidance in Sections 3.2 and 3.3 of this document. Radionuclide concentrations for intruder transport scenarios typically involve an estimation of environmental concentrations after release and transport through the disposal site environment. The release and transport are typically controlled by natural processes (e.g., degradation, sorption). The performance assessment for demonstrating that the requirements of 10 CFR 61.41 are met also estimates radionuclide releases from the source term of a disposal facility that are controlled by natural processes.

There are a few exceptions to the similarity between a performance assessment and an intruder assessment. First, access points for the intruder to the contaminated environmental media should all be on site. Offsite exposures are assessed in the performance assessment for demonstrating that the performance objective for protection of the general population is met. Second, intruder receptor scenarios are typically independent. For example, the intruder who contacts the waste during construction of a dwelling may not be the same individual who lives in the dwelling. The radiological exposures from these receptor scenarios are generally mutually-exclusive and not additive. However, there may be some cases in which it would be appropriate for receptor scenarios to be dependent. For example, it would be reasonable to assume that a well is installed to supply water to a dwelling that is constructed on the site and that the intruder residing in the dwelling is also exposed to contaminated ground water from the well. When dependent receptor scenarios are used and one is a direct contact scenario and the other is a migration scenario, the licensee may provide a basis for including the removal of some of the waste from the disposal cell at the time of the intrusion event in order to calculate releases from the buried waste for the transport scenario. Licensees should also assess the transport of waste that was accessed by the intruder (i.e., the transport of radionuclides from waste that was excavated by the intruder).

Reviewers should verify that the source term modeling is consistent with and appropriately integrated with other model abstractions (e.g., climate and infiltration for advective-diffusive release mechanisms). Reviewers should consult Section 3.1 for guidance on reviewing source term models involving advective-diffusive release mechanisms. Reviewers should evaluate the assessment of concentrations for the direct contact scenario and transport scenario to ensure that biases or assumptions in one of the scenarios don't result in an unreasonably optimistic approach in the other scenario.

4.3.2.3 *Transport*

Radionuclides directly contacted by an inadvertent intruder or released from disposal units may be transported in the general environment by groundwater, surface water, air, and biota (e.g., rodents). Model abstraction for transport processes in an intruder assessment is generally similar to model abstraction for transport processes in a performance assessment. Therefore, the guidance in Section 3.2 of this document is generally applicable to an intruder assessment. One notable exception is that an intruder assessment is focused on exposures on site. Therefore, model abstraction of transport processes should be focused on onsite transport processes for an inadvertent intruder assessment. This may include gaseous diffusion of radionuclides from the disposal unit through the overburden to an intruder at the surface or leaching from the disposal units and transport via groundwater to the intruder well at the site boundary. Radionuclides released from the disposal units that are transported beyond the site boundary (i.e., off site*)* are generally evaluated in a performance assessment for members of the public and would not need to be considered in an inadvertent intruder assessment.

4.3.2.4 *Dose*

The objective of the dose modeling in an inadvertent intruder assessment is to provide estimates of potential doses to an inadvertent intruder, in terms of the average member of the critical group, from direct contact with disposed waste or onsite releases from an LLW disposal facility after the period of active institutional controls. In this role, dose modeling integrates the information from the various modeling areas. In general, dose modeling in an intruder assessment is similar to dose modeling in a performance assessment. Dose modeling consists of converting radionuclide concentrations in environmental media to dose through various exposure pathways. Guidance on development of receptor scenarios is discussed in Section 2.2.4.2 of this document, and guidance on the dosimetry parameters is discussed in Section 2.2.4.3. Additional guidance applicable to modeling of exposure pathways in intruder assessment are discussed in the following sections.

The exposure pathway models link the radiological source, transport of radionuclides within environmental media, receptor location, and behaviors of the receptor that lead to its exposure to radionuclides through direct exposure, inhalation, and ingestion of contaminated water, soil, plants, and animal products.

Reviewers should evaluate the conceptual models that describe the human behaviors that lead or control the amount of receptor exposure. Therefore, the occupational, behavioral, and metabolic parameters describing these models should be reviewed and compared with the receptor scenarios and associated parameters.

In some cases, either the location of the disposed waste, the physical characteristics of the site, or the facility design may make the generic exposure pathways inappropriate. In other cases, the licensee may wish to provide a transparent and traceable development of the receptor scenarios used to demonstrate the performance objectives are met starting with potential land use and site-specific conditions. Development and review of alternate scenarios may involve iterative steps, including the development of the conceptual model of the site. For example, the licensee may (1) develop a generic list of exposure pathways, (2) develop the site conceptual model to screen the generic list, (3) aggregate or reduce the remaining exposure pathways to the major exposure pathways, and (4) reevaluate the conceptual model to verify that all the necessary processes are included.

A brief summary of the NRC-recommended process for exposure pathway analysis follows:

(1) Compile a list of exposure pathways applicable to any site containing radionuclides. There are a number of existing sources of information that can be used; e.g., NUREG/CR-5512, Volume 1 (NRC, 1992); NUREG-1757, Volume 2 (NRC, 2006); NUREG/CR-5453, "Background Information for the Development of a Low-Level Waste Performance Assessment Methodology," Volumes 1 and 2 (NRC, 1989b; NRC, 1989c); and the International list of Features, Events, and Processes (SSI, 1996).

(2) Categorize the general sources of radioactivity at the site (e.g., mixed in sediment or soil, groundwater).

(3) Screen out pathways for each source of radioactivity that do not apply to the site.

(4) Identify the physical processes pertinent to the remaining pathways for the site.

(5) Separate the list of exposure pathways into unique pairs of exposure media (e.g., source to groundwater). Determine the physical processes that are relevant for each exposure media pair and combine the processes with the pathway links.

(6) Reassemble exposure pathways for each source type, using the exposure media pairs as building blocks, thus associating all of the physical processes identified for the individual pairs with the complete pathway.

A licensee's documentation of the decisions made about inclusion or exclusion of the various pathways should be transparent and traceable. If any of the pathways studied are found to contribute less than 10 percent of the total dose limit in 10 CFR 61.42, that pathway does not need to be evaluated in detail. However, the sum of the doses from all the pathways that are excluded from more detailed evaluation should be accounted for in the demonstration that the performance objective is met. If there are alternative, equally reasonable receptor scenarios for a particular site, then the significance of the exposure pathways needs to be screened and analyzed for each scenario. This approach is needed because pathways determined to be insignificant based on one scenario may not be insignificant for other equally credible scenarios.

4.4 Institutional Controls

As required in 10 CFR 61.23(g), a licensee must provide reasonable assurance that institutional controls will be provided for enough time to protect the general population from releases per 10 CFR 61.41, to protect individual inadvertent intruders per 10 CFR 61.42, to assure that radiation standards in Part 20 will be met per 10 CFR 61.43, and to provide long-term stability of the disposed waste and disposal site per 10 CFR 61.44. In the context of inadvertent intrusion, institutional controls are used to limit intruder access to, and/or use of the site for a period of time following transfer of the disposal site to the owner and cannot be relied on for more than 100 years under 10 CFR 61.59. An institutional control program includes legal mechanisms (e.g., land use restrictions), environmental monitoring, periodic surveillance, minor custodial care, or other requirements as determined by the Commission, as well as the administration of funds to cover the costs for these activities. For the purposes of the intruder assessment, the institutional control period is separated into an “active” and “passive” period. During the active period, which cannot be relied on for more than 100 years, monitoring, surveillance, and custodial activities may be assumed to be carried out by the site owner. During this period, licensees may assume that the institutional controls are durable and will preclude inadvertent intrusion from occurring at the disposal site. The passive period follows the active period, and during this period it should be assumed that relatively few custodial activities are carried out. Inadvertent intrusion is expected to be unlikely due to the passive-period legal mechanisms, but is possible after 100 years, consistent with 10 CFR 61.59.

5.0 SITE STABILITY ANALYSES

The regulations at 10 CFR 61.50 require that LLW disposal sites should not be susceptible to erosion, flooding, seismicity, or other disruptive events or processes to such a degree or frequency that compliance with the 10 CFR Part 61 performance objectives cannot be demonstrated with reasonable assurance. The regulations at 10 CFR 61.44 also include a performance objective for disposal site stability after closure. It states that the disposal facility must be sited, designed, used, operated, and closed to achieve long-term stability of the disposal site for the compliance and protective assurance periods and to eliminate, to the extent practicable, the need for ongoing active maintenance of the disposal site following closure. This section focuses on the types of information expected to be associated with the stability demonstration required by the regulations, including consideration of the potential effects of erosion, flooding, seismicity, and other disruptive processes. This section also addresses stability of the wasteform as well as other engineered features that might be used at a particular LLW disposal facility.

Stability is the capability of the wasteform, disposal containers, disposal site, and disposal facility to maintain their shape and properties to an extent that the disposal action will meet the 10 CFR 61.41 and 10 CFR 61.42 performance objectives. Stability is defined in the regulation as “structural stability”. However, the impact of instability is not solely the change in shape and properties of the system. The change in shape and properties of the system may affect other FEPs associated with safety. Stability is important to:

- minimize changes to the disposal system that may result in increased releases of radioactivity to the environment as a result of increased infiltration (10 CFR 61.7)
- limit erosion and similar processes (10 CFR 61.50)
- ensure waste is recognizable by an inadvertent intruder (10 CFR 61.7)
- protect an inadvertent intruder by maintaining an appropriate overburden over the waste (10 CFR 61.7)

The NRC strategy for waste disposal is to “concentrate and contain” the LLW for as long as it remains hazardous. A key feature of that regulatory strategy is that components of the LLW disposal system must maintain stability. Stability ensures that once waste is emplaced and covered, access to the waste by water, biota, or humans is minimized, reducing the potential exposure to the public.

Many of the early problems associated with LLW disposal arose from site stability issues primarily associated with water (NRC, 2007b). To address these problems, a number of practical regulatory requirements, such as waste segregation requirements, were introduced to the regulations to obviate or limit future problems associated with waste stability (NRC, 1982a). Disposal of long-lived waste can increase the disposal challenge associated with ensuring waste stability, relative to short-lived LLW. For long-lived waste, it may be difficult to demonstrate the performance of the engineered features used to ensure waste stability, because the service life of those features is relatively short compared to the time those wastes remain hazardous. Site stability, in addition to the physical and chemical stability of the waste itself, can affect the performance of the waste disposal facility. Instability can be initiated by internal or external phenomena. NUREG-1200 provides details about site stability focused on waste stability, erosion protection, and geotechnical issues (slope stability, settlement, subsidence) (NRC, 1994). The guidance in this document is not a substitute for the information found in NUREG-1200; it can be used to supplement NUREG-1200, in particular for the site stability analyses associated with long-lived LLW. Within this guidance document, the term “site stability” is used to refer to the overall stability of the LLW disposal system, which includes stability of the waste, disposal site, and disposal facility and surrounding environment, as applicable.

The discussion in this section is divided into the following topics: disruptive processes (i.e., hazards), technical assessment, and engineered barriers. After a licensee identifies and characterizes potential disruptive processes, they can use different technical assessment methods to understand the impact of the disruptive processes on the ability of a disposal site to meet the performance objectives. Licensees can use technical assessment to evaluate if the hazards can be reduced or even mitigated. The technical assessment for site stability does not need to be complex (see Section 5.2.2). Screening analyses may be appropriate. In addition, it may be possible to mitigate the impact of some hazards using engineered barriers. Long-term evaluation and monitoring of the site can be used to confirm if site stability can be achieved. If the monitoring calls into question whether site stability can be achieved, licensees can propose a mitigating engineering action to enhance stability. The technical assessment may also determine that the candidate site is not suitable for the disposal of certain concentrations and quantities of LLW. Consequently, it may be necessary to impose limits (see Section 7.0) on the concentrations and quantities of LLW suitable for disposal at the proposed site. Similarly, the material itself may not be suitable for near-surface disposal under the 10 CFR Part 61 regulations. An overview of the main elements of site stability analyses is provided in Figure 5-1.

Stability and uncertainty are interrelated topics. Site stability analyses should be developed and evaluated in a risk-informed manner. Section 61.44 requires that site stability must be demonstrated for the compliance and protective assurance periods. As timeframes increase, the uncertainty associated with site stability increases. In addition, the scope and diversity of phenomena that may impact the stability of the disposal site increases. As previously noted, stability is to be applied in the context of meeting the performance objectives for 10 CFR 61.41 and 10 CFR 61.42. However, site stability is an independent performance objective (10 CFR 61.44). Uncertainty associated with high instability may limit the ability of a licensee to demonstrate that 10 CFR 61.41 and 10 CFR 61.42 can be met. Inventory limits may be used to mitigate the uncertainties associated with potential instability, or to prohibit disposal of waste that remains hazardous when the instability is projected to occur.

Section 61.50 of 10 CFR Part 61 provides the disposal site suitability requirements used in the site selection and evaluation process. Licensees can use site selection to eliminate or greatly reduce the number of disruptive processes and events that may need to be considered in the site stability analysis. For example, alluvial fans that form at the base of mountain ranges tend to be particularly unstable landforms over the long-term (NRC, 1983b).

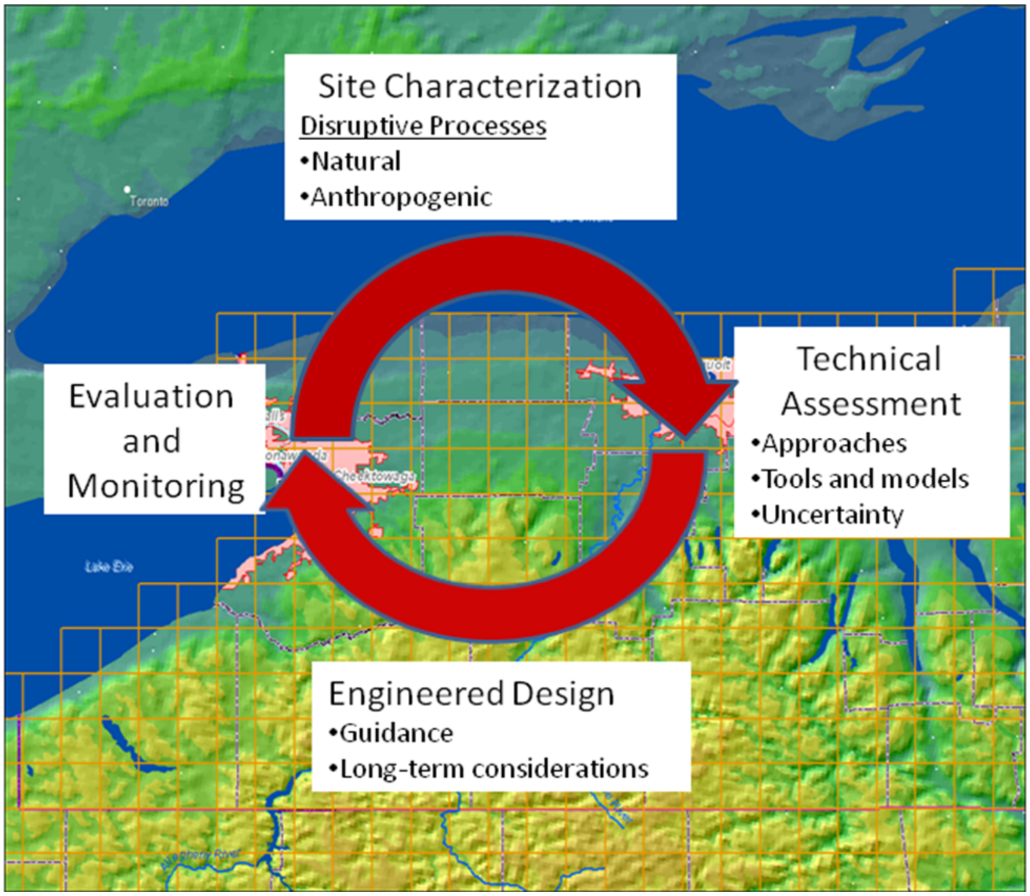

Figure 5-1 Main Elements of Site Stability Analysis

The impact of some events may be impossible to design against, given current technology and understanding (e.g., volcanism), and therefore, should be avoided. Other processes and events may be unavoidable (e.g., erosion, large precipitation events) and may be mitigated through site selection and engineered design.

Most, if not all, of the requirements listed in 10 CFR 61.50 were developed to ensure site[1] stability, as well as to allow licensees and reviewers to evaluate the performance of the site with reasonable assurance (NRC, 1982a). Site suitability requirements are separated into hydrological characteristics (10 CFR 61.50(a)(2) and 10 CFR 61.50(a)(3)) and other characteristics (10 CFR 61.50(a)(4)). 10 CFR 61.50(a)(2) specifies hydrological characteristics that a disposal site must have for a 500-year timeframe following closure of the disposal facility (e.g., not be located in a 100-year flood plain). 10 CFR 61.50(a)(3) specifies that after the 500-year timeframe following closure of the disposal facility, if any of the negative disposal site hydrological characteristics listed in 10 CFR 61.50(a)(2) are present (e.g., groundwater

[1] The terminology used in 10 CFR Part 61 is that waste is emplaced in a *disposal unit*. The disposal units, area between units, plus the surrounding buffer zone is the *disposal site*. The disposal site plus the other buildings, structures, equipment, and land used to complete disposal operations is the *land disposal facility* or disposal facility. In this guidance document, the term *disposal system* is used to refer to the disposal facility and surrounding environment

discharge to the surface), that they shall not significantly affect the ability of the disposal facility to meet the Subpart C performance objectives of the regulations.

The other site suitability requirements in 10 CFR 61.50(a)(4) specify characteristics of the site that should not be present such that they significantly affect the ability of the disposal site to meet the performance objectives of Subpart C (e.g., population growth, tectonic processes). The requirements in 10 CFR 61.50(a)(4) can exclude a potential disposal site location only if the FEP in question (e.g., tectonic processes, see Section 2.0) may prevent the performance objectives from being met, or if defensible modeling is precluded. For FEPs that result in severe disruption, defensible modeling may be precluded, and licensees, in concert with their regulators, may need to establish conservative inventory limits to mitigate the associated uncertainties. Practical solutions, other than numerical modeling, to limiting the impact of uncertainties associated with the disposal of long-lived waste may be necessary. Requirements associated with specific FEPs associated with site stability are provided in 10 CFR 61.50, including, but not limited to, the following:

- Areas must be avoided where tectonic processes such as faulting, folding, seismic activity, or volcanism may occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of Subpart C of this part, or may preclude defensible modeling and prediction of long-term impacts. [10 CFR 61.50(a)(4)(iii)]

- Areas must be avoided where surface geologic processes such as mass wasting, erosion, slumping, land sliding, or weathering occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of Subpart C of this part, or may preclude defensible modeling and prediction of long-term impacts. [10 CFR 61.50(a)(4)(iv)]

Site stability analyses should be tailored to the types of waste disposed. A facility designed for what might be regarded as traditional LLW streams (i.e., short-lived waste and low concentrations or quantities of long-lived waste) will have comparatively less complex site stability analyses than a facility designed for large quantities of concentrated, long-lived waste. For example, higher quality rock and more detailed testing and assessment of the durability of rock used for erosion protection will be needed for long-lived waste (compared to short-lived waste). Site stability analyses have three areas of focus: stability of the wasteform, stability of the engineered disposal facility, and geologic/geomorphic stability of the disposal site. For disposal of traditional LLW, site stability analyses will likely focus on the former two areas. For disposal of large quantities of long-lived waste, the focus will likely be on the latter two areas. The areal extent of the site stability analyses will be strongly influenced by the type of waste to be disposed. Stability of wasteforms, disposal units, engineered barriers (such as cover systems), disposal site, disposal facility, and disposal system may all be within the scope of the stability assessment.

The scope of the analyses needed for the site stability evaluation will be defined primarily by the type of waste and secondarily by the disposal system. The type of waste (i.e., short-lived or long-lived) will determine the timeframe appropriate for the site stability assessment, and therefore, what types of FEPs a licensee should evaluate. Waste disposal systems are generally reliant on passive features of the site geology/hydrology to limit long-term releases of radioactivity. To limit short-term releases, waste disposal systems may be strongly reliant on the performance of engineered systems. Passive systems, in general, will be more resistant to failure from unlikely natural events than active systems. Figure 5-2 provides an integrated view of the NRC staff's perspective on the temporal and spatial scales as well as the relative influence of various processes on site stability for LLW disposal.

The NRC staff developed Figure 5-2 based on the experience with assessments of LLW disposal facilities and complex decommissioning sites. Waste disposal facilities have not experienced frequent unlikely natural events (which are defined relative to the operating experience base) because the experience base is limited to the last half century. There is not enough data to quantitatively define the relative importance of the relevant processes.

Figure 5-2 is a generalization; however, the relative importance of a particular process at a specific site may differ from the conceptualization shown in the figure primarily as a result of location of the site. For instance, based on historical data, glaciation at a southern state would be expected to be of lower relative importance compared to glaciation at a northern state. Individual processes may also be dynamic such that the relative importance is not constant over time. The relative importance of climate could change based on the magnitude of effects of anthropogenic processes on climate change. With these types of caveats, the general expectation of the relative influences of various processes on site stability is:

1) In the near term (left hand side of the figure), erosion is expected to be the dominant process impacting stability. Secondary processes are biologic and climate. Igneous and tectonic phenomena are expected to be insignificant for a properly selected site. Glaciation is not anticipated in the near term.

2) In the medium term (middle of the figure), erosion is still of primary importance, but changes to climate which can impact erosion or result in glaciation at some sites become more significant.

3) On the long term (right hand side of the figure), most processes are expected to be important to evaluate in the stability assessment. As time increases, the likelihood of a large, low frequency seismic or volcanic event occurring increases.

4) The overall significance of various processes on site stability increases as time progresses. Over long timeframes, there is a higher overall likelihood that site stability will be affected by one or more of the processes.

A variety of resources are available to facilitate the development or review of site stability analyses. This section attempts to consolidate and summarize some of these resources but does not attempt to replicate them. The reader of this document should consult the original documents for more detailed information, as needed.

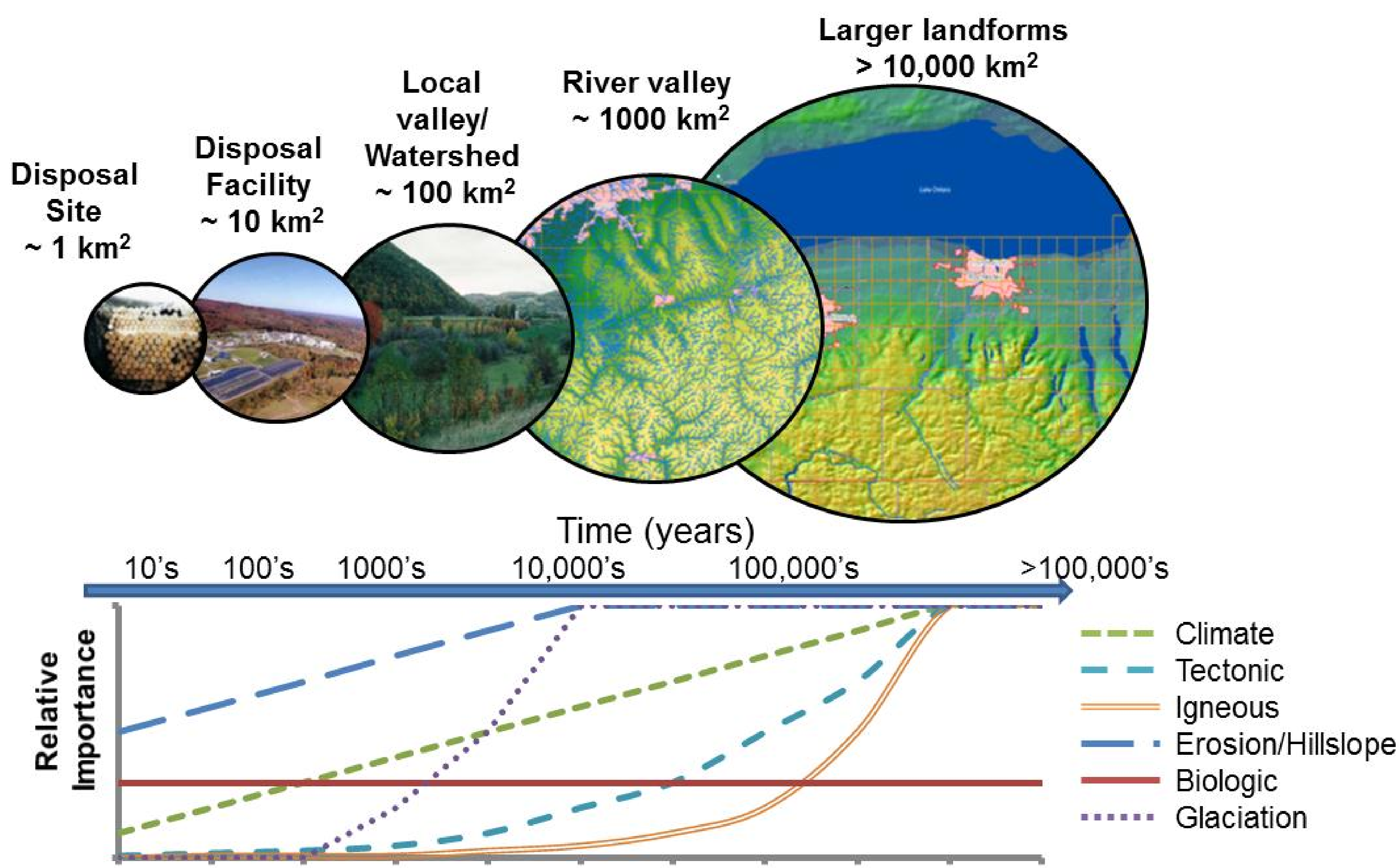

Figure 5-2 **Spatial and Temporal Scales and NRC Staff Perspective on the Relative Importance of Various Geomorphological Processes Relevant to LLW Disposal.**

Note: The time on the figure is comparable to the persistence of the hazard of the waste

5.1 Disruptive Processes and Events

A number of disruptive natural and anthropogenic processes and events could impact the long-term stability of a waste disposal system. Section 2.5 discusses the FEP screening process that licensees could use to identify disruptive processes and events that need to be evaluated in the site stability assessment. This section describes the information that a licensee should provide and a reviewer should evaluate with respect to identifying potential disruptive processes and events. The NRC staff expects the disruptive processes important to the estimation of the stability of an LLW disposal site to be site-specific.

The following primary elements are associated with the evaluation of disruptive phenomena:

- Which disruptive phenomena need to be evaluated?
  - What screening process will be used?
  - What criteria will be used for screening?

- How may the phenomena influence each other (i.e., are they correlated, dependent, independent)?

- Can the frequency and consequences of the events or processes impact the demonstration of compliance with the performance objectives of 10 CFR Part 61, Subpart C?

Licensees should describe in the site stability analysis the screening process that will be used to evaluate which disruptive phenomena to consider and the criteria used for the screening. Some natural phenomena will be expected to occur while others will be unlikely or very unlikely. The likelihood that a phenomenon occurs will be related to the timeframe of the evaluation; as explained in Section 2.3.2, the timeframe evaluated in the analysis is dictated by the type of waste that is disposed. Longer timeframes will result in higher likelihood that low-frequency events may occur over the timeframe considered.

The NRC staff recommends that licensees evaluate reasonably foreseeable disruptive conditions from natural events or processes in the site stability analysis. Reasonably foreseeable disruptive conditions include both those expected to occur and events that are moderately unlikely to occur (approximately 10 percent or greater chance of occurring) over the analyses period. The reasonably foreseeable disruptive conditions should be consistent with the characteristics of the waste. In other words, if the radiological inventory of the disposal site is primarily short-lived with low concentrations of long-lived radionuclides, it would not be necessary to look at reasonably foreseeable disruptive events based on the 10,000-year protective assurance period. A licensee could justify a shorter period, consistent with the characteristics of the radiological inventory. However, lower frequency events will need to be considered for higher concentrations of long-lived inventory. NUREG/CR-3964 (NRC, 1989d) provides examples of techniques that licensees can use to investigate and then determine the likelihood of certain natural events or processes that might be disruptive to the performance of an LLW disposal facility over the analyses timeframes.

The LLW intruder analysis required by 10 CFR Part 61 (see Section 4.0) often mitigates the need to consider low frequency disruptive events by bounding their projected dose impacts.

Intruder analyses typically bound the dose from a disruptive event because less dilution and dispersion is expected in a LLW intruder analysis, and the resultant contact with disturbed material is more direct than what would be expected for low-frequency natural events, which are typically highly energetic (e.g., a volcanic event). Thus, in many cases, the dose to the intruder may bound the impact from unlikely disruptive events. However, if a licensee does not estimate the impact to intruders from the generic receptor scenarios (i.e., they use site-specific scenarios), then they will need to evaluate the impact from unlikely disruptive events, which may drive overall performance.

Licensees should use a screening process to determine which processes and events need to be considered in the stability analysis. Processes and events can be screened out of the assessment based on probability, consequence, risk-based criteria (i.e., the combination of probability and consequence), or regulation (see Section 2.5.3.1.2). Screening based on probability typically establishes a cutoff frequency below which disruptive events are not considered further. This cutoff frequency is expected to be higher for LLW analyses compared to HLW analyses because the consequences of disruptive events are likely to be less severe for less-concentrated waste than for HLW. Screening of disruptive processes and events based on consequence or risk should consider the integrated effect of the process or event. For example, the growth of trees and eventual tree fall on a cover may not significantly impact the stability of the cover from the event itself, but it may create a depression to initiate future gullying. In many cases, there is limited experience, and therefore, limited understanding of potential combined phenomena. Although the uncertainty associated with combined phenomena cannot be reduced, the use of multiple independent peer reviewers with diverse backgrounds can reduce the likelihood of omitting important combined effects.

5.1.1 Natural Processes

The near-surface environment is continually evolving, influenced by processes as well as by discrete events. The processes and events may interact, compounding or reducing the effects observed from the individual phenomena. The systems are dynamic and may include positive or negative feedback effects. The phenomena most likely to impact the stability of a disposal facility, and therefore, the demonstration of compliance with the performance objectives of 10 CFR Part 61, Subpart C, will be specific to the particular site and design. This section covers different types of natural processes that can impact disposal facility stability. Geomorphic (e.g., mass wasting, erosion, slumping, land sliding, or weathering), tectonic (e.g., faulting, folding, seismic activity, or volcanism), biologic (e.g., animal or plant intrusion), or other processes and events (e.g., flood, fire, or extreme weather) may impact the future stability of waste disposal facilities. Processes and events may impact stability either directly (e.g., a large flood) or indirectly (e.g., a fire that disturbs vegetation, leading to increased erosion). In general, geomorphic processes will be the most likely stressors of long-term performance for most facilities.

Geomorphology is multidisciplinary, combining aspects of hydrology, climatology, ecology, and geology. Landform evolution is the sequence of processes and events that shape a given landscape. Landforms are built through tectonic, volcanic, and sedimentation processes and reduced through such processes as erosion and mass wasting. Evolution of landforms is associated with the balance between additive and subtractive processes. For long-term assessments, site stability analysis of geomorphological processes will likely entail integration of the effects of many of the processes described in the following sections.

Site characterization and selection will play an integral role in assessing natural processes that may impact the stability of the disposal facility. For new sites, applicants should characterize the site to define the geomorphic, tectonic, and other hazards that may significantly impact site stability. For existing sites that want to accept new waste, additional site characterization may be needed if the waste is materially different (e.g., more long lived) from previously accepted waste.

5.1.1.1 *Geomorphic Processes*

Geomorphic processes, such as mass wasting, slumping, land sliding, erosion, sinkhole formation, and weathering, may impact the stability of an LLW disposal facility. A description of the geomorphology of the site, including USGS topographic maps that emphasize pertinent local geomorphic features, may be useful to identify processes, such as erosion, that may affect long-term site stability. Erosion and weathering, in particular, are especially applicable to LLW disposal. Fluvial (at more humid sites) and eolian (at more arid sites) erosion of engineered covers is a common disturbance mechanism for disposal of long-lived waste. To mitigate certain geologic processes, licensees may achieve long-term erosion protection with robust engineered designs using a system of erosion controls and durable, appropriately sized rock (NRC, 2002b). Long-term erosion protection is protection for thousands of years to possibly a few tens of thousands of years. To achieve such long-term protection, the erosion controls should be independent and redundant, and the rock should be resistant to weathering. Avoidance of steep slopes and the use of low relief designs can reduce the impact of some geologic processes (NRC, 2002b). As discussed in Section 5.3, licensees may consider engineered barriers to mitigate the impact of many geologic processes.

The NRC staff expects erosive processes (fluvial and eolian) to be the most likely of all of the disruptive processes to impact the long-term stability of most disposal facilities. Therefore, the NRC staff recommends licensees develop robust erosion control designs using durable materials, as discussed in Section 5.3. Robust erosion control designs are usually developed based on the consideration of low-probability events, such as the PMP and corresponding PMF (NRC, 2002b). The PMF is defined as the hypothetical flood that is considered to be the most severe flood reasonably possible, based on (1) comprehensive hydrometeorological application of the PMP, and (2) other hydrologic factors favorable for maximum flood runoff, such as sequential storms and snowmelt. The return period of the PMP has been debated in technical literature because there are few direct observational data. A comparison of PMF peaks with historic floods in the United States yielded nine floods that exceeded 80 percent of the PMF but none that exceeded the estimated PMF (Bullard, 1986). Similar data compiled for approximately 20,000 gauging-station-years did not yield a flood that exceeded the calculated PMF (Crippen and Bue, 1977). For specific streams, paleo-flood data may be available to provide confidence that the computed PMF estimate is appropriately conservative. The return period associated with the PMP has been estimated from one statistical analysis of historical data at approximately 60,000 years (Koutsoyiannis, 1999). Koutsoyiannis cited the work of others that estimated the return period of the PMP to be from 200,000 to 1×10^9 years, using different approaches. The NRC staff considers the PMP to be a very unlikely event with respect to LLW disposal and that the PMP is appropriate to use to produce a conservative design.

The general approach used to assess geomorphic processes will involve three general steps: (1) identification of past geomorphic processes and estimation of their rates from stratigraphic and geomorphic records; (2) identification of present geomorphic processes and estimation of their rates from historic records and field observations (roughly the last 100 years); and (3) prediction of future processes and rates, accounting for uncertainty. Schumm and Chorley (NRC, 1983c) identified over 25 geomorphic processes that can create hazards at waste disposal sites. Typically, only a few of the hazards may be of concern at a particular site. A geomorphic hazard assessment will typically include the site and the surrounding region. An assessment of the surrounding region may provide information on processes that are occurring beyond the boundaries of the site but that may eventually extend onto the site. For example, the rate of migration of a river channel near a disposal site may give an indication that the river channel may eventually migrate onto the disposal site. In addition, the presence of a dam upstream from a facility may influence the frequency or likelihood of flooding, or result in flooding if the dam were to fail. Therefore, licensees should use information from the surrounding region to help estimate rates and magnitudes of processes that are not currently occurring at the disposal site.

It should be noted that a site does not necessarily need to experience mass loss; a site may be located in an accreting environment. Accreting environments are more favorable to <u>long-term stability</u> as nature enhances the isolation of the waste from the environment by covering the disposal facility over time. However, certain depositional processes may degrade the performance of some types of erosion controls (such as diversion channels). Licensees may use diversion channels at a site in an accreting environment to limit fluvial erosion and ensure site stability. Even in a net depositional environment, the site may experience periods of both deposition and erosion.

5.1.1.2 *Tectonic Processes*

Tectonic processes that can lead to long-term processes or events such as faulting, seismicity, or volcanism, may impact the stability of an LLW disposal facility. Nevertheless, a variety of factors should make tectonic processes generally less significant than the aforementioned geomorphic processes. First, licensees should use the site selection and characterization process to avoid areas of high tectonic activity. Second, LLW facilities are generally passive buried systems that are more susceptible to gradual deterioration from degradation and weathering than to discrete failure due to unlikely tectonic events. An exception would be facilities that rely significantly on engineered barriers to meet the performance objectives, especially resistive engineered barriers. A resistive engineered barrier is one that is reliant on physical properties to prevent liquid flow or transport, such as a geomembrane or cementitious barrier. A significant seismic event could result in cracking that would impact the ability of the engineered barrier to limit water flow. The durability of the engineered barriers would need to be assessed, as discussed in Section 5.3.

Licensees should assess the potential for subsurface geologic processes, such as faulting or seismic activity, to affect the site and proposed disposal facility. They should review historically recorded seismic information including recurrence intervals, magnitudes, and durations, as well as factors that contribute to peak ground acceleration, such as underlying geologic structures (e.g., active faults) and the stratigraphy and lithologies of the site. Licensees should evaluate the predicted effects of seismic events on waste isolation. Reviewers should evaluate any aspects of the disposal system designed to mitigate the potential effects of seismic events on waste isolation. Additional guidance on reviewing information related to seismic events in waste disposal is provided in NUREG-1804 (NRC, 2003c).

5.1.1.3 *Other Disruptive Processes*

Other natural processes and events can significantly impact the stability of an LLW disposal facility. These may include, but are not limited to, climactic processes and climate change, biological processes, and fires.

Climate and climate change have the potential to impact the stability of the disposal site. The impact of natural cycling of the climate could range from minimal to severe, depending on the location of the disposal facility. The type of waste that is disposed can influence how disruption from climate and climate change should be included in the assessment. Climate change can result in changes to the magnitude and duration of precipitation events, modification of the number of freeze-thaw cycles, or other effects.

For conventional LLW inventory, licensees should limit unnecessary speculation about severe climate change, such as glaciation. This type of event is envisioned as broadly disrupting the disposal site region. For conventional LLW, the hazard from the inventory remaining after 500 years is expected to be relatively low. The dispersion and dilution associated with the glaciation would further reduce doses. For LLW inventories that have low concentrations of radioactivity, the impact from waste that has been disturbed by severe climate change would likely be small compared to the impacts on humans from the event itself (i.e., the non-radiological consequences should outweigh the radiological consequences). However, it is still useful to communicate the sensitivity of the traditional LLW disposal facility performance to less severe changes in climate, such as changes to annual average precipitation and temperatures.

For LLW inventories containing long-lived isotopes, the hazard from the inventory remaining after 500 years may be significant. Therefore, licensees may need to evaluate the impact of climate change on the disposal site taking into account reasonably conservative scenarios. Climate change may not be gradual and continuous, as evidenced by a wide variety of published information (Alley, 2000; Fricke, 1993; Jenkyns, 2003). The rate of change may be just as important to establishing the risk as the magnitude of change. As previously discussed in Section 2.0, the site suitability requirements do not allow for selection of sites where instability precludes defensible modeling or assessment of long-term impacts.

Licensees should examine plausible scenarios for site evolution and characteristics in the site stability analysis. For example, the erosion rate under a future, wetter climate may be significantly larger than the present day. It should be noted that even small erosion rates can amount to substantial thicknesses in the long term (e.g., a 0.5 mm/yr rate will reduce a cover's thickness by half a meter in 1,000 years). However, the NRC staff believes that the magnitude of the PMP and PMF is not likely to change significantly in a wetter climate, based on the conservatisms associated with the estimation of the PMP and the PMF.

Biological processes can impact the stability of the waste and the stability of the disposal system. Biodegradation can affect the stability of waste containers and result in deterioration of the wasteform, which can result in instability of the disposal system. The BTP on wasteform describes test procedures and criteria to evaluate wasteform stability (NRC, 1991b). Biointrusion into the waste, or into engineered covers over the waste, can increase infiltration to the waste and contribute to the instability of the disposal system. Plants and animals may create pathways in resistive barriers. The disruptive effects of biological processes tend to be gradual but can be significant in some systems. Evapotranspiration or water balance covers can depend strongly on vegetation to eliminate water. Therefore, licensees should consider the impact of invasive species that have different root depths or growing patterns and water usage on site stability and on the performance assessment. Climate change may affect pedogenesis (i.e., soil development processes) and the type of cover vegetation. Fires, severe storms, and ecological succession due to changing temperature and precipitation could influence the ability of the vegetation to resist wind and water erosion and maintain a sufficient depth of cover over the waste.

LLW facilities are generally not highly sensitive to the impact of fires, such as brush fires. However, as mentioned above, vegetation can play an important role in reducing soil loss and maintaining site stability, in particular for slopes and covers. Under extreme conditions, fires may change the physical properties of the site soils and other cover materials. Strong fires have been shown to impact durability of select rock types (e.g., silica based minerals deteriorate after exposure to high temperatures) (Dorn, 2003). However, researchers at DOE's Hanford Site directly evaluated the impact of fire on an engineered cover system and found the impact to be minimal for their particular cover materials (Ward et al., 2009).

5.1.2 Anthropogenic Processes

Human activity may influence site stability both directly and indirectly. An example of a direct influence is construction of a dwelling on the disposal facility. An example of an indirect influence is acid rain generation, which could impact the durability of erosion control materials. The intruder assessment examines the direct impact to an inadvertent intruder who unknowingly disturbs the waste disposal facility. A licensee does not need to evaluate indirect impacts associated with human activity at the disposal site because they would be difficult to define and highly speculative. In addition, the direct impacts to the intruder should, in most cases, bound the impacts to the general public (offsite) from anthropogenic disruption of the disposal facility because there is comparatively less dispersion and dilution in the assessment of impacts to the intruder, so the direct impacts will be greater. However, if site-specific intruder scenarios are used that result in relatively limited exposures, then indirect processes may dominate the risk and should be examined. A licensee does not need to consider anthropogenic climate change, but should consider natural cycling of climates, if necessitated by the analysis timeframe for their waste disposal actions. Section 4.0 provides guidance for performing the intruder assessment.

5.1.3 Subsidence and Differential Settlement

Subsidence and differential settlement are very important for all types of waste disposal because instability of the disposal site can result in unacceptable releases, regardless of the overall stability of the disposal facility. Differential settlement was a key failure mode in earlier LLW disposal sites, prior to the passage of 10 CFR Part 61 (NRC, 2007b). Subsidence and differential settlement can lead to unacceptable releases because the processes can adversely affect barrier performance (e.g., cracking of an engineered cover, creating a depression in the cover resulting in localized ponding).

Subsidence and differential settlement can result from a variety of different processes and events such as:

- Excessive void space in the waste or backfill
- Lack of compaction or improper compaction of waste, backfill, engineered or natural materials
- Degradation of wasteforms, engineered barriers, and other structures
- Improper waste emplacement
- Alteration of natural materials (e.g., collapse of subsurface zones)
- Excessive or uneven loading of the disposal site or engineered cover
- Interaction of the disposal system with water

Some designs may be more susceptible to subsidence and differential settlement than others (e.g., designs that combine robust cementitious barriers with unconsolidated and uncompacted natural materials may be particularly sensitive). Subsidence and differential settlement are covered in sufficient detail in NUREG-1199 an NUREG-1200 and additional guidance is not provided in this document (NRC, 1991a; NRC, 1994). These documents detail relevant site characteristics, construction and operations phase data, experiment and test data, modeling, and remedial actions.

5.2 Technical Assessment

Some form of technical assessment will be used to complete the site stability analysis. The technical assessment should provide an assessment of the stability of the wasteform, the disposal facility including waste containers and other engineered barriers, and the site. The level of detail and type of assessment used will be dictated by the specific waste, the complexity of the site and facility, the hazard being mitigated, and the uniqueness of the problem. Probabilistic or deterministic analyses may be used by licensees as long as uncertainty and variability are assessed.

5.2.1 Available Tools and Codes[2]

A number of tools and codes are available to licensees to support site stability analysis. Recent advances have resulted in a vast array of technologies available to facilitate analysis of the near-surface environment. Licensees are encouraged to use the best available information for their assessments. The field of geomorphology has evolved quite significantly over the last half century and numerous technologies are available today to facilitate site stability analysis (Kondolf and Piégay, 2005). Although the preponderance of tools is focused on near-term and small-scale evaluations, a number of tools and techniques have been developed to look at the longer-term and large-scale. Tools such as optical dating, image analysis, pollen analysis, paleomagnetic dating, oxygen isotopes, lithologic analysis, vegetation surveys, tree-ring analysis, archives, and radioisotopic dating have been used to study the evolution of the near-surface environment (Anderson and Anderson, 2010).

[2] NRC does not endorse or recommend any specific code or model for site stability analysis. Licensees are free to select and justify their particular code or model for their application. Regardless of the code selected, it is important that the code meet all applicable quality assurance requirements.

Walter and Dubreuilh (2007) evaluated computational approaches used to simulate engineered cover performance and degradation. They evaluated 21 computer codes, which they categorized as hydrologic codes, erosion codes, and miscellaneous codes. The erosion codes were further categorized as generalized erosion codes, localized erosion codes, and mass wasting codes. The generalized erosion codes generate estimates of the average soil loss due to water or wind erosion from a plot of land. The localized erosion codes simulate soil loss at specific locations, and some can simulate landscape evolution that may be important to long-term site stability. Table 5-1 provides a summary of the erosion and mass wasting computer codes, including their applicability and limitations for long-term site stability analysis (Walter and Dubreuilh, 2007). The review by Walter and Dubreuilh (2007) does not represent an exhaustive list of available computer codes; however, it may be useful to licensees to identify the types of tools that are available and their limitations.

The University of Colorado and partners have created the Community Surface Dynamics Modeling System (CSDMS) that provides (1) a modular modeling environment capable of significantly advancing fundamental earth-system science, and (2) fully functional and useful repositories for models, supporting data, and other products for educational and knowledge transfer use (Syvitski et al., 2011). The CSDMS repository contains more than 160 models and tools. The system includes 66 codes and 41 tools associated with terrestrial modeling. Landscape evolution (CHILD, SIBERIA, Caesar, Erode, GOLEM, MARSSIM, and WILSIM), eolian transport (Eolian Dune Model), and cryosphere (GC2D, ISGR, Ice Ages) codes are included.

5.2.2 Approaches for Assessment

Licensees may use a variety of technical assessment methods to perform site stability analyses. Because of the site-, facility-, and waste-specific nature of site stability analysis, the tools and assessment techniques used may differ considerably from site to site.

The approaches may be design-based, model-based, or a combination of the two. Modeling may play a more significant role for analysis of longer timeframes, due to the limited data to support long-term performance of stability designs. It is important that licensees provide a technical basis for the site stability analysis, regardless of the approach used. The technical basis will likely be more extensive for analysis of longer timeframes than for shorter timeframes. Model support is essential for site stability analysis. Licensees should develop model support throughout the process, although the largest effort (comparable to model validation) is usually completed at the end of the process. Model validation in the traditional usage is not possible for analyses over long timeframes. Iteration may be necessary.

Table 5-1 Summary of Applicability and Limitations of Erosion and Mass Wasting Codes for Long-Term Performance Assessment Evaluated in Walter and Dubreuilh, 2007

Code	Process Representation	Calculation of Cover Loss and Topographic Change
RUSLE	Empirically-based using correlations from test plots, requires empirical data to simulate future cover conditions	Computes areally-averaged soil loss, independent calculations required to compute changes in cover thickness
EPIC	Empirically-based using correlations from test plots, requires empirical data to simulate future cover conditions, but more versatile than RUSLE by calculating soil water balance	Computes areally-averaged soil loss, independent calculations required to compute changes in cover thickness
WEPP	Physics-based approach to erosion allows flexibility in representing future soil cover conditions based on fundamental properties	Computes areally-averaged soil loss, for multiple hill slopes, independent calculations required to compute changes in cover thickness
EUROSEM	Physics-based approach applied over two-dimensional topographic surface allows representation of complex topography including future changes in topography	Computes distributed soil loss within model domain with a fixed topography, independent calculations required to compute change in surface elevation and cover thickness
LISEM-Gullies	Empirically-based approach to soil loss and gully formation over two-dimensional topographic surface but limited to single storm events	Calculates gully formation and associated changes in topography during single storm events, multiple simulations required to evaluate long-term performance
SIBERIA/CHILD	Physics-based approach applied over two-dimensional topographic surface allows representation of complex topography including future changes in topography	Calculates changes in elevation and topography based on soil loss and deposition, including soil creep and slumping
WESS	Empirically-based wind erosion code with limited process documentation	Computes areally-averaged soil loss, independent calculations required to compute changes in cover thickness
WEPS	Physics-based wind erosion code with ability to represent topographic and wind-break effects	Computes areally-distributed soil loss, independent calculations required to compute changes in cover thickness
LISA	Simple, physics-based calculation of sliding potential with stochastic output	Computes sliding potential, but not topographic change
DLISA	Simple, deterministic, physics-based calculation of sliding potential	Computes sliding potential, but not topographic change

The authors of the codes listed can be found in Walter and Dubreuilh (2007)

The site stability assessment should include the following general steps:

(1) Site description — Provide a description of the features of the site, facility, and waste associated with stability. At a minimum, licensees must provide information required by 10 CFR Part 61, Subpart D (technical requirements for land disposal facilities). As previously discussed, 10 CFR 61.50(a)(4)(iii) and 10 CFR 61.50(a)(4)(iv) provide specific requirements with respect to tectonic and geologic processes. The site description can include geologic and geomorphic characteristics that contribute to site stability. The site description may also include geologic, geomorphic, and tectonic hazard assessments.

(2) Overall initial radiological risk screening — It may be possible to demonstrate, with a conservative evaluation, that release of radioactive material, as a result of potential instability, will not result in sufficient radiological risk (i.e., that the 10 CFR 61.41 and 10 CFR 61.42 performance objectives can still be met). If so, site stability analysis may be limited to providing the screening assessment. In other words, a licensee can satisfy 10 CFR 61.44 if its screening assessment provides reasonable assurance that 10 CFR 61.41 and 10 CFR 61.42 will be met under disturbed conditions. Licensees should select receptors and scenarios consistent with the guidance provided in Section 2.2.4 and Section 4.0. The screening assessment should be sufficiently conservative to account for uncertainty.

(3) Process and event screening — Perform screening of disruptive processes and events (consistent with guidance provided in Section 2.5). Processes and events can be screened out of the assessment based on probability, consequence (as indicated in Step 2 above), or risk-based criteria. Risk-based criteria combine probability and consequence. Screening of disruptive processes and events based on consequence or risk should consider the integrated effects of the processes or events, as discussed in Section 5.1.

(4) Define scope of the assessment — The FEPs that cannot be screened out from the site stability analysis should be used to define the scope of the assessment. Licensees can compile the processes and events that cannot be screened into scenarios. They can inform the scope of the assessment by considering the operating experience of analogous sites and facilities. If there is uncertainty about whether a process or event should be included, the NRC staff recommends erring on the side of inclusion. It is generally more difficult to add processes and events at a later date in the analysis process than it is to remove them from the assessment.

(5) Characterize information — Use the site description to determine what data are available to complete the assessment and to identify the significant sources of uncertainty. The type of information available is likely to depend on the timeframe being analyzed. Interpretation of the available information, with the characteristics of the waste, disposal facility, and site, will inform the approach that should be used for the assessment (e.g., model-based or design-based). The purpose of this step is to determine how much information is available to support the assessment completed in Step 6.

(6) Perform assessment — The assessment may be performed with a model-based approach (generally for long-lived wastes), a design-based approach (for short-lived or

long-lived wastes), or a combination of the two. The NRC staff expects that licensees may use modeling to assess and develop designs. The steps provided below may be completed in a different sequence. However, regardless of the order, most assessments will include the following steps:

a. Design-Based:

i. Define the design objectives.
ii. Develop or select the design.
iii. Document and provide the basis for assumptions.
iv. Characterize or parameterize the design.
v. Assess the expected performance of the design.
vi. Provide support for the design.
vii. Iterate, if necessary.

b. Model-Based:

i. Define the model objectives.
ii. Develop or select the conceptual model.
iii. Document and provide the basis for assumptions.
iv. Develop the numerical model.
v. Parameterize the model.
vi. Calibrate the model.
vii. Verify the model.
viii. Characterize uncertainty.
ix. Provide model support.
x. Iterate, if necessary.

The elements listed above for design-based or model-based approaches are not unique to site stability assessment for LLW disposal. Many information sources are available to provide additional guidance, such as Section 2.0 of this document and NUREG-1573. In addition, licensees may mix elements from design-based and model-based approaches. For example, Appendix P of NUREG-1757 provides a description of how to risk-inform the design-based approach. Risk-informing the design-based approach involves performing technical analyses, such as sensitivity analyses, to test the robustness of the design to unanticipated events and processes.

(7) Integrate — The site stability assessment will likely need to be integrated with the performance assessment required by 10 CFR 61.41 and the intruder assessment required by 10 CFR 61.42. If stability can be assured, then the level of integration is minimal. However, if instability is projected, then licensees will need to evaluate the significance of that instability in the performance assessment and intruder assessment. For example, degradation of an engineered cover via erosion may lead to increased water infiltration to waste in a disposal cell. The releases estimated in the performance assessment should include nominal performance, as well as releases attributed to instability of the waste, the disposal site, and the disposal facility. When the stability assessment is based on both design and modeling, it is also important for a licensee to document that the design has been integrated into the stability modeling.

(8) Iterate (if necessary) — It is likely that some amount of iteration will be necessary in the site stability assessment. There are likely to be many sources of uncertainty, including some that were unanticipated initially in the design or modeling process.

5.2.2.1 *Design-Based Approach*

A licensee may use a design-based approach to site stability analysis to demonstrate site stability for the associated timeframe. The design-based approach has been used successfully for the management of uranium mill tailings, though the experience base is only tens of decades. Section 5.3.2 presents information on analogs that suggests longer-term performance should be achieved. Appendix E provides an example of the use of the design-based approach to develop erosion protection measures for the management of uranium mill tailings. Section 5.3 of this document provides guidance on the use of engineered barriers for site stability assessment. A licensee may use the guidance provided in Section 5.3, or alternatively, may develop their own approach as long as the technical content of the steps listed in Section 5.3 is included. Designs may use risk information, however, to mitigate long-term uncertainties, conservative, robust designs may be beneficial irrespective of projected risk information. The design-based approach may be supplemented with sensitivity analyses in order to better characterize and understand uncertainties (see NUREG-1757, Volume 2, Revision 1, Sections 3.5.2 and 3.5.3). The following steps outline the design-based approach.

Define the design objectives. The primary design objectives are the time period over which stability must be achieved and what instability, if any, is tolerable in order to ensure compliance with the 10 CFR Part 61 Subpart C performance objectives. Waste characteristics and the risk to the public, including an inadvertent intruder, will be the drivers of the design objectives. For example, a licensee that wishes to dispose of only short-lived waste and small quantities of long-lived waste may achieve protection of public health and safety by ensuring waste stability for 500 years. The licensee may be able to demonstrate that insufficient radioactivity remains in the disposal system to pose an unacceptable risk to a member of the public after that time.

Develop or select the design. After defining the design objectives, the licensee should develop the design or select a design that has previously been demonstrated to achieve their objectives. Because of the site-specific nature of LLW disposal, even previously utilized designs are likely to require modifications for site-specific application. Section 5.3 presents information on rock durability, for example, that is strongly influenced by local environmental conditions. Section 5.3 provides an acceptable process for selecting erosion protection materials.

Document and provide the basis for assumptions. Assumptions are a common part of design and analysis. A licensee should document and provide a basis for assumptions that they have used in developing or selecting their design. Regulators should review the documentation and determine if adequate technical bases for the assumptions have been provided. Assumptions should be internally consistent.

Characterize or parameterize the design. After a licensee has developed or selected a design, they may need information in order to characterize the features of the design or provide parameters that will be used to represent the performance of the design. For example, a design may use natural and engineered materials. The licensee may need to consider the weathering or degradation rate of those materials. The licensee may need to perform and document experiments used to develop the design information, such as the thickness of a reactive wall.

Sufficient documentation should be provided to allow for independent verification of the results. If a licensee uses information from generic sources to parameterize the design, they should demonstrate that the information is relevant to the site-specific application.

Assess the expected performance of the design. Verification of the design involves technical assessment of the performance of the design over the range of disruptive processes and events expected to influence the design. A licensee should clearly identify over what range of conditions the design is expected to perform and over what range of conditions the design may fail. This information is useful to regulators and other stakeholders if future conditions are to occur that may have been unforeseen during the design process. A licensee or regulator may use independent confirmatory analyses or modeling in order to verify the design.

Provide support for the design. A licensee must provide adequate support for the design prior to implementation of the design. Types of support for engineered designs are similar to the types of support provided for models, as discussed in Section 2.2.3 (e.g., tests, experiments, field studies, and analogs). In addition, support for designs may also include the experience base for the particular design, such as the number of locations where it has been used and for how long. Unique or novel designs, which may be necessary for particular applications, are not to be discouraged but they will have additional uncertainty as to whether they will achieve the design goals. A licensee should provide additional support for the performance of a novel design compared to what would be provided for a standard design that is expected to perform for a similar time period. The support for the design at the time of implementation will not have information from the actual performance of the design. Therefore, the overall design process may need to be iterative as monitoring and performance confirmation data are collected.

An example of a design-based approach to erosion protection is described in NUREG-1623, "Design of Erosion Protection for Long-Term Stabilization". In addition, Appendix P of NUREG-1757 provides a description of how to risk-inform the design-based approach. NUREG-1623 was developed to provide methods, guidelines, and procedures that the NRC staff considers to be acceptable for designing erosion protection at uranium mill tailings sites (NRC, 2002b). These design approaches are based on technical procedures and design parameters that are widely used in the engineering community and by other Federal agencies and have been applied at various disposal sites.

5.2.2.2 *Model-Based Approach*

A licensee may also use a model-based approach for performing the site stability analysis for the associated timeframe. The model-based approach is used to evaluate the FEPs that may affect the stability of the site and determine if the effects are significant. The model-based approach may determine that the impacts are:

- Insignificant - adequate site stability has been achieved irrespective of the FEPs associated with site stability, or
- Significant - site stability has not been achieved.

A licensee may undertake a variety of actions if site stability is not demonstrated. They may refine their modeling and the refined model may demonstrate that the projected FEPs have insignificant impacts. As a result of their modeling, the licensee could implement design changes to achieve stability, or they may conclude that the site does not have adequate stability to be suitable for the type of waste proposed for disposal at the site. Inventory limits may be used to mitigate the risks and uncertainties associated with site instability

The steps involved in the model-based approach to site stability assessment provided in Section 5.2.2 are similar to the steps to develop a performance assessment. Therefore, a licensee should review the guidance provided in Section 2.0 when using a model-based approach to site stability assessment. Appendix E provides an example of using a model-based approach to site stability assessment. As discussed in Section 2.2.3 and Section 5.3.2, model support is essential to any type of model-based approach. The NRC staff strongly recommends natural analogs and other forms of evidence of the long-term stability of the site.

A number of tools and codes are available to licensees to support site stability modeling. The field of geomorphology has evolved considerably over the last half century and numerous technologies are available today to facilitate site stability analysis, including various programs such as hydrologic codes, erosion codes, and landscape evolution codes (e.g., CHILD and SIBERIA). Although the uncertainties associated with such landscape modeling are often large, licensees can use modeling to gain insights and perform site stability assessments.

Licensees should consider the following technical issues when developing the scope of a model-based approach to site stability assessment:

- Changes to nearby stream beds and river channels in unconsolidated material may impact landform evolution.
- Given sufficient precipitation, large rain events, and time, the watershed of an area can change considerably. Specific parts of a facility may end up close to stream channels with an increased gradient, leading to accelerated erosion.
- Drainage patterns may change. For example, if variations in climate circulation patterns are great enough, regional drainage patterns may change.
- Erosion/deposition rates may vary spatially and temporally across the site.
- Long-term erosion often concentrates in gullies, which do not uniformly erode over their entire length. Peak erosion depth may translate into a total breach of a portion of the disposal facility.
- Evidence of the past natural history of the area, or from an appropriate natural analog, may be an indicator of future surface geomorphic processes.
- Pedogenic processes, biotic activities, and bioturbation are all processes that may impede or accelerate surface geomorphic processes. Thick root systems from certain plants are known to greatly reduce erosion; however, it is difficult to rely on the continuous presence of a specific plant that might be needed to ensure stability over longer timespans.
- A number of factors could influence flora, such as drought, fire, disease, fungi, and insects. Observed erosion rates may be tied to the presence of flora.
- Changes in the water chemistry and other environmental conditions may cause changes to properties of the rock responsible for physical and chemical stability.

5.2.3 Uncertainty

Uncertainty is inherent in the stability assessment of near-surface LLW disposal facilities and should be accounted for in the evaluation. Probabilistic assessment techniques are generally more amenable to accounting for uncertainty (see Section 2.7.4), although the NRC staff does not prescribe a particular technique. The site stability assessment should consider the general types of uncertainty (e.g., data, model) described in Section 2.0. A variety of techniques are available for handling uncertainty in multimedia environmental modeling (NRC, 2004c).

Site stability assessment may involve additional uncertainties that can be particularly challenging to characterize and understand. Some near-surface processes can display high sensitivity to initial conditions, such as the sensitivity of erosion rates to initial topography. There can also be feedbacks, both positive and negative, that can result in complex responses (Pelletier, 2008). The complex responses in turn translate into uncertainty in interpreting characterization and observational data. The complex responses can be difficult to understand; therefore, they can be difficult to implement in numerical modeling, which results in model uncertainty. Environmental systems can also exhibit sensitivity to the initial conditions as well as the pathway taken to arrive at the initial conditions (i.e., hysteretic phenomena). As discussed in Section 2.0, one approach to mitigate the impact of uncertainty is to use conservatism. For example, using the PMP/PMF for the design-based approach to erosion protection can result in a robust design.

Incorporation of information at variable temporal and spatial scales is a challenge in site stability analysis. Some processes or events may span orders of magnitude in temporal and spatial scales. The key to understanding complex systems often lies in understanding how the processes on different scales influence each other. Licensees may need to coarsen or upscale detailed information at finer scales, in order to perform numerical modeling at coarser scales. If upscaling is used, it is important to perform physical or numerical experiments that demonstrate that essential information is preserved in the upscaling process. In addition, it is important that data are representative for the scale and conditions being simulated. For example, a single point measurement of soil moisture content may not be representative of (1) a sitewide value, (2) a more global value, or (3) of the distribution of local values needed in a site stability analysis.

5.3 Engineered Barriers for Site Stability

This section of the guidance document describes the information that a licensee should provide and a reviewer should evaluate with respect to the use of engineered barriers for site stability. Engineered barriers are likely to be used for erosion control or may be used for other reasons such as to mitigate the impact of disruptive processes and events.

A surface cover is frequently utilized to provide physical stabilization of the site (10 CFR 61.44). The components of engineered barrier systems may include liners, covers or caps, and/or lateral barriers or walls. These systems may use a variety of natural material such as aggregates, soil, or clay, and synthetic, cementitious, and bituminous materials including polyethylenes, fabrics, mortar, and asphalt. The regulatory disposal requirements, and the type of engineered barrier system that a licensee chooses, depend on the waste type. Of all the components of a disposal system, the engineered surface barrier, or cover, is the most commonly used barrier and is often considered to be one of the most important components.

Since engineered surface covers can be significant barriers, they may provide reasonable assurance that one or more performance objectives will be met. Engineered covers may greatly contribute to disposal facility performance by minimizing infiltration and slowing degradation of the stabilized wasteform (10 CFR 61.41) and by providing an intruder deterrent (10 CFR 61.42).

5.3.1 Existing Guidance

The NRC staff believes that existing guidance developed for analogous programs (e.g., uranium mill tailings, decommissioning) is applicable to the design of engineered barriers for the stability of LLW disposal facilities. The processes and events that may disrupt LLW facilities are essentially identical to those that may impact a uranium mill tailings disposal facility or a decommissioned site. The main exception is that some LLW disposal facilities could contain higher concentrations and quantities of long-lived waste. Considerations for the design of engineered barriers for long-lived waste are provided in Section 5.3.2. Existing guidance is focused on cover design, particularly material durability. The focus of stability analysis in waste disposal has been on erosion protection. The NRC staff plans to periodically assess the sufficiency of guidance in this area and supplement it when necessary.

Engineered barriers are distinct and separate from institutional controls. Used in the general sense, an engineered barrier could be one of a broad range of barriers with varying degrees of durability, robustness, and isolation capability. Generally, engineered barriers are passive, man-made structures or devices intended to enhance a facility's ability to meet the performance objectives. Engineered barriers are usually designed to inhibit water from contacting waste, limit releases of radionuclides (e.g., through groundwater, biointrusion, or erosion), or to mitigate doses to inadvertent intruders. Engineered barriers can serve a variety of functions; therefore, they have markedly different technical considerations and designs. The NRC staff expects that the main type of engineered barrier used for LLW disposal will be engineered covers. Engineered covers can be further classified into conventional (resistive) covers and water balance (evapotranspiration) covers. Each of these types of covers may have erosion control functions. The following sections further discuss these types of covers.

Section 3.5 of NUREG-1757, Volume 2, provides guidance on a risk-informed, graded approach to the design and evaluation of engineered barriers (NRC, 2006). High-level guidance on engineered barriers is provided in NUREG-1573 for general application to LLW disposal. NUREG-1573 contains a bibliography organized by different topics, including Appendix C on engineered and natural barriers. There are a broad range of engineered barriers for stability, with varying degrees of durability and robustness. Engineered barriers for LLW disposal stability should be passive (i.e., they should perform without reliance on active monitoring and maintenance). Licensees should provide an appropriate technical basis for engineered barriers providing significant performance. The following steps are the main steps of an appropriate technical basis for engineered barriers, as described in NUREG-1757:

- Describe the design, features, and functionality of the engineered barriers.
- Provide the technical basis that the performance of the barriers will allow a licensee to demonstrate that the performance objective will be met, considering the degradation mechanisms, including consideration of combined and synergistic effects resulting from the real-world conditions expected for the barriers.

- Describe uncertainty in parameters and models used in the assessment of barrier performance and the design of engineered barriers.
- Demonstrate the suitability of numerical models for the estimation of engineered barrier performance.
- Perform parametric or component sensitivity analysis to identify how much degradation of the engineered barrier would result in noncompliance.
- Provide model support for the engineered barrier performance (e.g., analogs, experiments, engineering calculations to demonstrate reasonableness of the results).
- Provide QA/QC for the data collection, design, construction, and analysis of engineered barriers.

These steps apply to engineered barriers used to support demonstration of compliance with 10 CFR 61.41 and 10 CFR 61.42, as well as for site stability. Model support for engineered barrier performance is essential. Model support, as discussed in Section 2.2.3, can come in many different forms, including but not limited to analogs, laboratory experiments, field experiments, and formal and informal expert judgment. The basis for why a barrier is expected to perform the desired function is essential for a licensee and other stakeholders to have confidence in the future performance of the barrier. For engineered barriers that are estimated to have long-term performance (e.g., thousands of years), licensees should consider natural analogs in order to provide confidence that the estimates are reasonable. Extrapolating short-term observations to estimate long-term performance can result in a significant uncertainty in long-term barrier performance. Standard approaches implicitly assume that the initial conditions persist; however, the actual application of a barrier may be more appropriately viewed as an evolving component of a larger dynamic system (Waugh and Richardson, 1997). In addition, inaccurate conceptualization of degradation mechanisms and their interaction can be a source of significant error. Adequate model support can help reduce the impact of these uncertainties. NUREG-1757 provides examples of analogs for cement performance (wasteform stability), durability of earthen covers, and riprap durability (site stability) (NRC, 2006). NUREG-1757 also summarizes the degradation mechanisms of common engineered barriers, including engineered covers such as resistive covers, water-balance covers, and erosion control covers. Section 3.5.5 of NUREG-1757 provides a summary of reference information related to engineered cover design and performance.

One of the most common barriers used to ensure stability in waste disposal facilities, especially for near-surface disposal of long-lived waste, is an erosion protection cover. As mentioned in Section 5.2.2.1, NUREG-1623 may be useful to licensees because it provides methods, guidelines, and procedures that the NRC staff considers to be acceptable for designing erosion protection at uranium mill tailings sites (NRC, 2002b). The main elements to developing an engineered barrier for erosion protection in waste disposal are:

- Selection of proper rainfall and flooding events
- Selection of appropriate parameters for determining flood discharges
- Computation of flood discharges using appropriate and/or conservative methods
- Computation of appropriate flood levels and flood forces associated with the design flood discharge

- Use of appropriate methods for determining erosion protection needed to resist the design discharge
- Selection of a rock type for the riprap layer that will be durable and capable of providing the required erosion protection for the required timeframe
- Placement of riprap layers in accordance with accepted engineering practice and in accordance with appropriate testing and quality assurance controls

The NRC staff considers that the guidance provided for design of erosion protection systems for management of uranium mill tailings is applicable to the stability of LLW disposal facilities, and may be used for nearly all types of erosion protection designs. However, for high concentrations and large quantities of long-lived waste (as discussed in Section 5.3.2), licensees should place greater emphasis on rock durability, and additional considerations may be necessary. Erosion protection designs may take many different forms. Many designs use a durable rock cover; however, some combine vegetation or employ multiple layers of differing materials (i.e., a composite cover) or rock mulches.

The main design considerations of an erosion protection cover using rock can be separated into two main areas: (1) appropriate sizing of the rock, and (2) assurance of the durability of the cover materials. NUREG-1623 provides methods for sizing rock for an erosion protection cover (design based on the PMP). Licensees should size the rock to ensure it will stay where it is placed; they should then ensure that the rock will not degrade significantly (i.e., it will stay close to its initial size). In order to maintain its design size, appropriately sized rock should not experience significant mass loss from weathering or experience significant cracking.

Rock durability is defined as the ability of a material to withstand forces of weathering. Factors that affect rock durability are (1) chemical reactions with water, (2) saturation time, (3) the temperature of the water, (4) scour by sediments, (5) windblown scour, (6) wetting and drying, and (7) freezing and thawing. Chemical weathering and mechanical weathering may reduce the effectiveness of a rock cover for erosion protection. Chemical weathering is generally a slow, continuous process that usually occurs in the presence of water. Mechanical weathering is a process that can lead to deterioration of the rock without chemical alteration. The most prevalent mechanical weathering processes are (1) frost action and freeze-thaw activity, (2) salt crystallization, migration, and hydration, (3) water sorption, (4) mineral hydration, (5) wetting and drying cycles, (6) abrasion by wind, water, and mechanical means, and (7) temperature-induced expansion and contraction of mineral grains (NRC, 1982c). Comparing the latter processes with the factors that affect rock durability demonstrates that mechanical weathering is a dominant degradation process. The individual weathering mechanisms are likely to be specific to the rock type selected and the weathering processes at the site. Weathering processes and rates are strongly influenced by climatic conditions. Figure 5-3 provides a macroscale relationship of climatic variables, environments, and rock weathering agents.

An engineered cover for LLW disposal may have more than one design goal. For example, in addition to providing site stability, the engineered cover may be used to reduce infiltration. Licensee should ensure all design goals are achieved realizing that some decisions may have competing influences on the design goal. For instance, using large rock may promote site stability but may increase infiltration compared to other erosion protection designs such as using rock mulch.

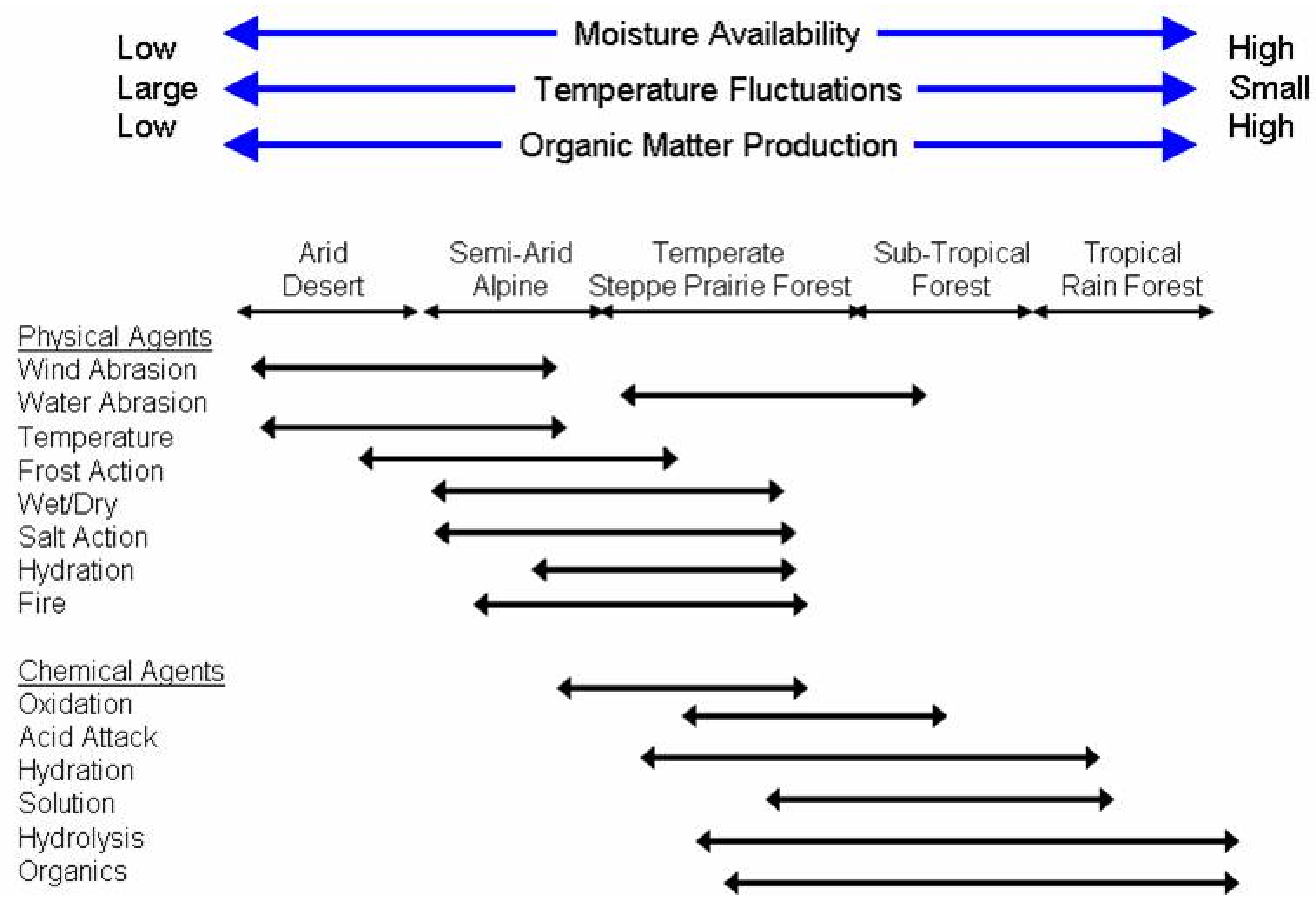

Figure 5-3 Macroscale Relationship between Climatic Variables, Environments, and Rock Weathering Agents: Occurrence of Weathering as a Function of Climate (NUREG/CR-2642)

As discussed in Appendix P "Example of a Graded Approach for Erosion" to NUREG-1757, a licensee should conduct three evaluations of rock durability to provide multiple and complementary lines of evidence and greater confidence in rock durability. The three evaluations are for (1) rock durability testing and scoring, (2) absence of adverse minerals and heterogeneities, and (3) evidence of resistance to weathering.

First, licensees should conduct rock durability testing and scoring. They should test and evaluate potential rock sources to ensure that rock used for erosion protection remains effective for the required timeframe. NUREG-1623 (NRC, 2002b) presents a procedure for determining the acceptability of a rock source. In general, rock durability testing is usually performed using standardized test procedures, such as those developed by ASTM and published and updated in ASTM's *Annual Book of ASTM Standards.* The scoring procedure indicates that rock scores of 80 percent or greater indicate a high-quality rock for most applications (e.g., decommissioning sites for 1,000 years). Long-lived waste would generally require very high-quality rock, higher than necessary for most decommissioning applications.

Second, the absence of adverse minerals and heterogeneities is essential. Licensees should use analyses (such as petrographic analyses) to establish the absence of adverse minerals that could cause rapid degradation of the rock, such as clays, olivine, or calcite cement. If adverse minerals are present, licensees should evaluate their potential effect on the weathering of the rock and on weathering rates.

Third, licensees should provide evidence of resistance to weathering, using direct evidence from the selected rock source whenever possible. For example, weathering rind thickness and alteration of minerals and rock properties from exposures of the weathered rock source can provide insights on the extent and nature of future weathering. Table 5-2 provides general characteristics of rocks related to weathering resistance (NRC, 1982c). Some characteristics are favorable with respect to chemical weathering and unfavorable with respect to mechanical weathering, and vice versa. Indirect evidence from natural and archeological analogs should also be used, as discussed in Section 5.3.2.

5.3.2 Long-Term Considerations

Disposal of long-lived waste introduces additional complexity and uncertainty with respect to site stability. A disposal facility containing long-lived waste may be exposed to (1) more extreme conditions, as well as more cycles of extreme conditions, (2) greater uncertainty because of more limited performance and observational data, and (3) greater difficulty in obtaining relevant information. Because of the increased uncertainty inherent in longer-term predictions, the design of engineered barriers for stability of long-lived waste relies on conservative designs. Licensees should use the following elements in their design of engineered barriers for long-lived waste:

- multiple, independent, and redundant barriers
- conservative approaches
- very high quality and durable materials

Table 5-2 Weathering Resistance and Susceptibility Related to Weathering Type and Rock Properties

	Chemical Weathering		Physical Weathering	
	Durable	Nondurable	Durable	Nondurable
Mineral Composition	- Uniform mineral composition - High silica content - Low metal ion content (Fe-Mg), low biotite - High orthoclase, Na feldspars - High aluminum ion content	- Mixed/variable mineral comp. - High $CaCO_3$ content - Unstable primary igneous minerals - Low quartz content - High calcic plagioclase - High olivine	- High feldspar content - Calcium plagioclase - low quartz content - $CaCO_3$ - homogeneous composition	- High quartz content - Na plagioclase - Heterogeneous composition
Texture	- Fine grained dense rock - Uniform texture - Crystalline - Clastics - Gneissic	- Coarse-grained igneous - Variable textural features - Schistose	- Fine grained (general) - Uniform texture - Crystalline, tightly packed clastics - Gneissic - Fine-grained silicates	- Coarse grained - Variable texture - Schistose - Coarse-grained silicates
Porosity	- Large pore size, low permeability - Free draining - Low internal surface area	- Small pore size, high permeability - Poorly draining - High internal surface area	- Low porosity, freely draining - Low internal surface area - large pore diameter free draining	- High porosity, poorly draining - High internal surface area - Small pore diameter
Bulk Properties	- Low adsorption - High compressive and tensile strength - Fresh rock - Hard	- High adsorption - Low strength - Partially weathered rock - Soft	- Low adsorption - High strength with good elastic properties - Fresh rock - Hard	- High adsorption - Low strength - Partially weathered rock - Soft
Structure	- Strongly cemented, dense grain packing - Siliceous cement - Massive	- Poorly cemented - Calcerous cement - Thin bedded - Fractured cracked - Mixed soluble and insoluble minerals	- Minimal foliation - Clastics - Massive formations - Thick bedded sediments	- Foliated - Fractured, cracked - Thin bedded - Mixed soluble and insoluble minerals
Representative Rock	- Igneous varieties (acidic) - Metamorphics (other than marbles) - Crystalline rocks - Rhyolite, granite, quartzite, gneisses - Granitic gneiss	- Calcerous sedimentary - Poorly cemented sandstone - Slates - Limestones, basic igneous, clay-carbonates - Marble, dolomites - Carbonates, schists	- Fine-grained granites - Some limestones - Diabases, gabbros, some coarse-grained granites - Quartzite (metamorphic) - Strongly cemented sandstone - Slates, granitic gneiss	- Coarse-grained granites - Poorly cemented sandstone - Many basalts - Dolomites, marbles - Soft sedimentary - Schists

5.3.2.1 *Conventional (Resistive) Covers*

Licensees can use conventional covers for different design functions. However, with respect to site stability, the most likely use of a conventional cover is for erosion protection. Designs for sites with relatively short-lived waste are expected to be simpler than designs for sites with waste that will remain hazardous until or beyond the end of the compliance period. Design concepts for the end of the compliance period and for the performance period should include the use of oversized rock and overthickened rock layers, use of the PMF, and consideration of more stable structures such as low slopes and blending with local topography. By using multiple, independent, and redundant barriers licensees can reduce the impact from the unanticipated failure of a single barrier.

One example of the use of multiple barriers for an erosion control system could include one or more of the following types of erosion controls:

- The riprap layer for the top slopes and side slopes of the closure covers could be designed to resist the PMP and PMF.
- The top of the covers could be sloped to drain entirely in one direction, minimizing the flows that would enter gullies that form in areas that are not designed for drainage downstream of the covers.
- The site could be optimally graded to enhance drainage, and diversion channels could be constructed to convey runoff to noncritical locations.
- Downstream gullies could be armored with very large rock to prevent further gullying and nickpoint migration.
- Diversion channels could also be constructed upstream of the covers to divert flows away from the covers or from potential critical gully locations.

Licensees may need to consider the natural cycling of climates in the design for sites intended for long-lived waste disposal. In some locations (e.g., more northern), glacial and interglacial cycles may result in glacier development and migration over a LLW disposal facility. It is beyond current technology and understanding to design a near-surface facility to withstand such forces. In more northern locations, the assessment should focus on the risks following disruption of the design. Licensees may consider natural analogs to estimate the amount of waste dispersion associated with those processes, and therefore, the risk. Stylized, conditional dose assessments may also be useful. In more southern geographic locations, the impact of natural cycling of climates may be less severe and may be confined to effects such as increased precipitation and cooler temperatures (e.g., more freeze-thaw cycling). Licensees should examine the durability of erosion control materials over the range of projected future climate states. The use of the PMP and PMF for erosion protection design may mitigate the need to consider future climate states because these parameters represent maximum events. The PMP approach approximates the maximum rainfall that is physically possible, and the PMF is a hypothetical flood that is considered to be the most severe reasonably possible (NUREG-1623, p. 10). Climates that are arid now and more likely to be arid in the future are typically preferable over wetter climates. Low amounts of water reduce chemical and mechanical weathering.

Licensees should consider the following when selecting and justifying the long-term durability of erosion protection materials:

- Selection of highly durable rock—Select only a highly durable rock type with a mineral that is most resistant to chemical weathering, such as quartz. This would favor a metamorphic quartzite or a sedimentary orthoquartzite with a high percentage of quartz grains (99 percent) cemented by quartz. Rock types that can easily alter to clay over the timeframe considered, such as feldspars, should not be used. This may eliminate many rock types. Locally-available, highly durable rock is preferable because it has a higher likelihood of being in equilibrium with the disposal environment.

- Selection of a homogeneous rock source—Select a rock unit that will result in riprap pieces that are homogeneous and free of heterogeneities, such as bedding planes, thin shale layers, or joints. Heterogeneities that can allow access of water can contribute significantly to mechanical weathering, such as freeze-thaw.

- Reliance on natural analogs and weathering rate studies—Evaluate natural analogs and obtain applicable weathering rate studies, if available, to justify the durability of the selected rock.

    - Weathering rate studies: Obtain weathering rate study data over relevant timeframes, to the extent available, recognizing any uncertainties in the studies. Weathering rate data may be estimated from laboratory data complemented with field observations. If laboratory data are generated, use caution in extrapolating the data to field performance because mineral weathering does exhibit scale dependence (Drever and Clow, 1995). Weathering rates can also decrease exponentially with time, as the most vigorous attack usually occurs early in the weathering process. Comparative data on natural materials may help with material selection, such as that shown in Table 5-3 (Brookins, 1984) or in Table 6.7 of NUREG/CR-2642, "Long-Term Survivability of Riprap for Armoring Uranium Mill Tailings and Covers: A Literature Review" (NRC, 1982c). Comparative data show the relative durability of different materials in a common test. Various compilations of research on weathering rates have been developed (e.g., Colman and Dethier, 1986). Use weathering rate data that is representative of the estimated future exposure conditions because weathering rates can be very sensitive to exposure conditions. For example, one of Cleopatra's Needles (a granite obelisk) survived very well in over 3,000 years of exposure in arid conditions in Egypt but weathered heavily in under 100 years after being moved to New York City.

Table 5-3 Comparison of Chemical Durability (Soxhlet Test) of Waste Glass and Common Minerals

Minerals	Wt% Leached[1]
Quartz crystals	0.41
Milky quartz	0.50
Dolomite	0.55
HLW glass	0.70
Garnet	0.73
Corundum	0.77
Orthoclase	0.90
Granite	1.10
Quartzite	1.20
Felsite	2.10
HLW glass (devitrified)	2.50
Marble (dolomite)	2.90
Calcite	5.80
Basalt	6.10

Source: Brookins, 1984
[1] Represents mass loss in the Soxhlet test

- Natural analogs: Use natural analogs to provide confidence in the long-term durability of the materials selected. Use natural analogs for the specific rock type proposed and from the region of the disposal facility, instead of more distant examples, because local materials with demonstrated long-term durability will provide the most direct link to long-term performance. However, more distant examples may be useful to address the durability of the materials under a more diverse range of exposure conditions. Quaternary glacial striations on quartzites and dating of very old rock surfaces may also be useful. Research is ongoing using cosmogenic dating to estimate the ages of natural materials that have not weathered significantly over very long time periods. For long-term stability, engineered systems should mimic durable natural systems as much as feasible. The comparison of engineered systems to natural systems should address material properties as well as how the materials are emplaced and distributed to achieve stability.

  For a variety of reasons, certain Quaternary glacial features have the potential to be a very good source of natural analogs. The features of greatest potential value include glacial striations, polished rock surfaces, and glacial erratics. In particular, glacial striations (i.e., fine scratches on a bedrock surface that can be less than a millimeter in depth) and polished rock surfaces are delicate features that could easily be removed by weathering. Preservation of such vulnerable features over long time periods demonstrates a significant resistance of the rock to weathering. Glacial features (found in various climates today) are also fairly common in a range of different rock types, which makes them reasonably available for use as analogs. Glacial features have been exposed to a range of climates during the past thousands of years since their formation. Finally, licensees do not need to determine the precise age of the features in order to use them as a natural analog for a LLW facility. In the absence of available specific dating studies, a general assumption can usually be made that the features are the result of the last glacial period, which ended about 10,000 years ago. Fortuitously, the general 10,000 year age assumption coincides with the 10,000 year protective assurance period for a LLW facility.

- Historic analogs: Preliminary analyses and observations by the NRC staff and consultants have indicated that many manmade sites exist that demonstrate the long-term stability of both manmade structures and naturally occurring features. Many of these analog sites are located in the United States and consist of structures such as Native American earthen burial mounds, Native American ruins, and rock features. Many of these sites have been dated and have been shown to have remained intact for thousands of years. Licensees can use studies of the long-term survivability of such features to demonstrate the potential for manmade sites, such as LLW waste disposal facilities, to remain intact for very long periods of time without the need for ongoing active maintenance. For example, the Sarsen stones of Stonehenge may provide data for orthoquartzites.

The benefits of historic or archeological analogs are that the ages of rock carvings, monuments, or buildings are usually fairly well known and can demonstrate preservation under known climates and time periods. Furthermore, many potential analogs might be available for a range of rock types. While many of these analogs can demonstrate preservation for hundreds or thousands of years, the timeframe is less than the 10,000 year protective assurance period. However, if available, historic or archeological analogs can complement natural analogs by providing a variety of evidence that together increase the confidence in the ability of a rock type to resist significant weathering over long time periods.

Although direct evidence of material durability from the site or site region is preferable, licensees can also use indirect evidence from other locations where the general rock type is similar to the selected rock source, considering differences in environmental conditions. In some cases the durability may be sensitive to the exposure conditions while in other cases it may be less sensitive or insensitive. For example, licensees could use evidence of durability from a diabase igneous rock-type found in Europe to provide insights on a diabase rock-type source in Maryland because the general mineralogy of diabase is similar, regardless of the location. This approach allows the use of datable natural or archaeological and historical rock sites, which could provide general evidence of rock weathering rates or time periods during which rock types have remained resistant to weathering. For example, a licensee could use many datable archaeological sites, such as Stonehenge (constructed about 4,000 years ago of diabase and silica-cemented sandstone); Hadrian's Wall (constructed by the Romans over 2,000 years ago of primarily diabase); and numerous buildings, monuments, and megoliths in Europe, to demonstrate that these rock types have been resistant to weathering over time periods that exceed thousands of years.

Historical evidence can also provide useful insights on the durability of certain rock types. One example is the comparison of dated Civil War photographs of diabase outcrops in Devil's Den at the Gettysburg National Military Park to present-day conditions of the same outcrop. A licensee could demonstrate with such a comparison that this diabase has been resistant to weathering for about 150 years. Similarly, dated grave markers or historical buildings made from the selected rock source or a similar rock type can also provide evidence of resistance to weathering for 100–200 years. Appendix A to NUREG/CR-2642 provides additional information on rock weathering, durability, and examples of analogs that provide insights on general weathering rates of various rock types (NRC, 1982c).

A test wall of building stones was constructed in 1948 in Washington, DC and in 1977 it was moved to the National Institute of Standards and Technology in Gaithersburg, MD (Stutzman and Clifton, 1997). This test wall provides the opportunity to study the effects of weathering on different types of stones under identical exposure conditions and the durability of different materials. Imaging and petrological studies have been performed to characterize texture and mineralogy. Correlation of mineralogical and microstructural features to stone performance provides information for estimating the long-term durability of natural materials. The wall contains 2,352 individual samples of stone: 2,032 domestic stones from 47 States and 320 stones from 16 foreign countries. Over 30 distinct types of stones are represented, including marble, limestone, sandstone, and granite. Data from this project are limited at this time and are likely to be uncertain but may provide licensees another line of evidence for rock durability.

5.3.2.2 *Evapotranspiration Covers*

Evapotranspiration (ET) covers, use the natural processes of evaporation and transpiration to remove water from the cover. Although evaporation and transpiration can remove water from the conventional covers discussed in Section 5.3.2.1, it is primarily the layers of low permeable material present in the conventional covers that limit water from reaching the waste. In contrast, ET covers rely more heavily on evaporation and transpiration to limit water from reaching the waste. The performance of ET covers depends on many factors, especially the climate, soil hydrology, fauna, and plant ecology at a site. ET covers may be used in a variety of settings, but may be most effective in arid or semi-arid climates with high potential evapotranspiration.

Licensees should develop a design for an ET cover that is effective over the range of expected natural and ecological conditions. Natural and ecological conditions are inherently variable over the timeframe of most LLW disposal analyses. With effective design and development, ET covers may be very effective, especially in arid and semi-arid climates. In humid climates, ET covers may be effective at managing a substantial fraction of the infiltration but may not achieve design goals. Infiltration may exceed evapotranspiration in humid climates or in colder climates, where a large fraction of infiltration may occur as snowmelt when evapotranspiration is low. Therefore, one of the major lessons learned, albeit not related to physical degradation, is that design of an ET cover must consider natural and ecological variability over the analyses timeframe (Benson et al, 2011).

Licensees should be aware that physical, biological, and chemical processes can induce changes in the structure, physical, and biological characteristics of covers that are intrinsic to their proper functioning as barrier systems. Degradation processes occur over a broad range of time scales and include, but are not limited to, climatic variability, plant succession, geomorphic processes, pedogenesis, anthropogenic impacts, erosion, microbial processes that affect barrier materials and drains (e.g., biofouling), and geochemical processes. An example of unanticipated ecological consequences is the development of deeper rooted plant species that result in pathways for moisture that are below the design zone for moisture storage and removal.

Engineered systems evolve towards a natural equilibrium. Licensees should recognize that soil properties may change quickly, and therefore, should minimize the consequences of these changes by designing and constructing covers that mimic longer-term conditions that are congruent with nature. Cover degradation attributable to pedogenesis and ecological change should be recognized as an inevitable, fairly predictable, natural succession. In some cases, natural pedogenesis and ecological succession can lead to improved system performance over time. Therefore, performance will be steadier over time when licensees design engineered soil layers and vegetation to more closely resemble the characteristics of natural systems. A licensee should determine the function of each ET cover component (e.g., use of plants and their roots to stabilize the cover of a site). Licensees should develop techniques to understand the magnitude and direction of natural changes anticipated to occur. One approach is to evaluate natural analogs. General strategies that a licensee may use to minimize the negative impacts of degradation processes include:

(a) Attention to construction QA; QA is especially important to the successful short-term performance of the cover

(b) Identification of the phenomena that have the greatest impact on total system performance

(c) Analysis of each component within the system context

In addition, to increase confidence in the long-term stability of the site, the licensee should focus on: (1) using natural analogs to better understand and evaluate long-term degradation processes, including both spatial heterogeneity and temporal trajectories of change; (2) designing covers that mimic the favorable attributes of selected natural analogs; (3) evaluating effects of soil development and ecological change; (4) evaluating effects of waste subsidence on long-term cover performance; and (5) predicting and incorporating landform changes in cover and disposal cell designs (NRC, 2011b). In addition, the performance of an ET cover can be particularly sensitive to temporal and spatial variability in precipitation and other processes.

5.3.3 Monitoring of Engineered Barriers

Most waste containment facilities require monitoring to verify performance and/or support predictive modeling (NAS/NRC, 2007). Environmental monitoring of a LLW disposal facility is required for the duration of the institutional control period. The design of monitoring systems for engineered barriers has proven difficult as a result of technological challenges and complex goals; however, progress is being made. Observing the effects of degradation processes is critical to understanding long-term performance. Performance monitoring of engineered surface covers provides a licensee confidence that the cover is functioning as predicted in the performance assessment, intruder assessment, or site stability assessment.

Monitoring of engineered covers generally is conducted at two levels: direct non-destructive performance monitoring, and direct or indirect interpretive monitoring. Performance monitoring consists of directly and continuously monitoring the primary performance variable (e.g., the flux of water through a cover) using an in-situ device. Interpretative monitoring consists of measuring secondary variables (e.g., water content) related to the primary performance variable that can be used to understand or interpret data obtained from primary performance monitoring (NRC, 2011a). Interpretive monitoring can be conducted directly using embedded sensors or indirectly using remote sensing methods such as ground penetrating radar or airborne radar systems. Water content and temperature are the two most commonly measured secondary variables employed for interpretive monitoring. Interpretive monitoring currently is conducted almost exclusively using direct methods. However, indirect remote sensing methods likely will become more important in the future, especially for long-term monitoring from remote locations (NRC, 2011a).

During the period of institutional controls, licensees must perform environmental monitoring to ensure continued satisfactory disposal system performance and to develop confidence that the observed performance is likely to persist after the institutional control period. Licensees should also perform physical surveillance to restrict access to the site and minor custodial activities during the institutional control period. Short-term performance of the disposal site can be physically monitored with various types of onsite instrumentation or by remote sensing. Licensees can use monitoring to: detect any early significant releases of contaminants, and to verify the validity of assumptions made and the accuracy of the results of predictive modeling, thereby, reducing uncertainty. Though not required, the NRC staff strongly recommends that licensees conduct interpretive monitoring because it can provide observations of performance problems that are a precursor to releases of radioactivity into the environment.

Licensees should include assumptions, parameters, and features that have a large influence on the disposal facility performance and have relatively large uncertainties as an important part of a monitoring plan. For example, monitoring plant processes or more generally ecological processes, can add greatly to understanding cover stability and performance. Even carefully designed cover systems begin a process of change immediately following construction. These changes can affect containment system performance both directly and indirectly, and should be monitored. Additional information gained through various sources can reduce uncertainties and support previous predictive modeling. Monitoring is considered important in obtaining confidence that barrier components are performing as intended and is an important tool in detecting early signs of degrading stability of a disposal system. Because of increased understanding of potential shortcomings with engineered surface barriers, monitoring of engineered systems is being recognized as a powerful tool that has the potential to yield valuable data. A well-conceived monitoring system for engineered surface barriers would provide information to assess barrier performance including degradation.

Airborne and satellite-based remote monitoring techniques are able to efficiently monitor particular aspects of the engineered surface covers. For example, remote sensing may detect vegetative change that is dependent on characteristics of water flow. Linear features of heavier vegetation may be indicative of cracks or other structural features allowing increased contact of water with the waste and may be indirect signs that the overall stability of a barrier may be decreasing. Sensor development has rapidly advanced so that sensors are becoming not only quicker, more reliable, and longer lasting, but also smaller, more automated, wireless, and more sophisticated. Licensees can obtain changes in vegetation, soil water content and temperature through multispectral imaging. Ground penetrating radar, LIDAR (or Light Detection and Ranging technology), and other remote sensing techniques may detect stabilization problems at the very early stages due to its high resolution output (NAS/NRC, 2007). Licensees may someday be able to place automated sensors throughout the different components of the cover to monitor those features and processes demonstrated to be significant.

Licensees should not use monitoring as a substitute for the development of an adequate performance database prior to implementing their system, but rather to support the previous determination of adequacy considering uncertainty. When there is uncertainty associated with the waste disposal system, monitoring can maintain confidence in the performance demonstration.

Monitoring and modeling activities are complementary to one another. Modeling can serve to focus monitoring efforts by identifying key processes and parameters or disconnects between field observations and model results. Similarly, the results of monitoring provide feedback to refine models and improve the understanding of the system. Licensees should design their monitoring systems to understand processes and events and identify early indicators of performance problems.

6.0 PROTECTIVE ASSURANCE PERIOD ANALYSES

10 CFR 61.41(b) requires that:

> Concentrations of radioactive material that may be released to the general environment in groundwater, surface water, air, soil, plants, or animals shall be minimized during the protective assurance period. The annual dose, established on the license, shall be below 5 mSv (500 mrem) or a level that is supported as reasonably achievable based on technological and economic considerations in the information submitted for review and approval by the Commission. Compliance with this paragraph must be demonstrated through analyses that meet the requirements specified in 10 CFR 61.13(a).

10 CFR 61.42(b) requires that:

> Design, operation, and closure of the land disposal facility shall minimize exposures to any inadvertent intruder into the disposal site at any time during the protective assurance period. The annual dose, established on the license, shall be below 5 mSv (500 mrem) or a level that is supported as reasonably achievable based on technological and economic considerations in the information submitted for review and approval by the Commission. Compliance with this paragraph must be demonstrated through analyses that meet the requirements specified in 10 CFR 61.13(b).

The primary purpose of the protective assurance period analyses is to provide information that demonstrates that releases of radioactivity from a LLW disposal facility are minimized during the protective assurance period. Minimization is the reduction of doses to as low as reasonably practical with technical and economic factors taken into consideration. The protective assurance period is the period from the end of the compliance period through 10,000 years following closure of the site. This section provides guidance on developing the technical analyses for the protective assurance period.

The requirements for the protective assurance period differ from the compliance period in two respects. First, the requirement for 10 CFR 61.41(b) and 10 CFR 61.42(b) is minimization. As explained later in this section, minimization should not be interpreted to mean that zero release or zero risk can be achieved. Few activities are without risk; there must be a balance between the health and safety measures that are introduced to control risk and the costs arising or benefits forgone when these health and safety measures are introduced. Depending on the particular waste and the technical challenges associated with its disposal, the end point of the minimization process may correspond to different levels of risk or dose. Second, a target to compare the minimization against is provided in the regulation (i.e., 5 mSv (500 mrem)); however, other targets may be supported if they are reasonably achievable based on technological and economic considerations. The process of minimization typically involves a comparison of alternatives and could involve cost-benefit analysis. Generally, a preferred option is compared to various alternatives to justify that the preferred option minimizes impacts in a technically and economically practical manner. There are many different technical and programmatic options (e.g., an enhanced wasteform) that can be used to control risk. If impractical, not all of the combinations of these options need to be evaluated; however, each of the main technical options should be evaluated. Section 6.1 provides guidance on developing the scope of the analyses for the protective assurance period. Section 6.2 discusses the conceptual framework for the analyses, presents different types of analyses that may be considered by licensees, as well as the NRC staff's recommended approach for applying long-term discounting to LLW disposal. The minimization process and associated metrics are also described.

6.1 Scope of the Protective Assurance Period Analyses

Protective assurance analyses are an extension of the technical analyses used to evaluate disposal system performance during the compliance period. The results of the performance assessment, intruder assessment, and site stability assessment provide the technical basis to demonstrate that impacts to the general population and inadvertent intruders have been minimized.

The assumptions, data, and models used to develop the compliance period technical analyses will be sufficient for the protective assurance period analyses unless changes are necessary to address the uncertainties associated with the longer timeframes. If scientific information is available, or can be developed in a cost-effective manner, then the compliance period assessments should be enhanced or modified. The FEPs that were represented in the compliance period analyses will generally apply to the protective assurance period, although the frequency and magnitude may vary temporally. Section 2.5 provides guidance on developing the scope of the technical analyses.

6.2 Framework for the Protective Assurance Period Analyses

The analyses for the protective assurance period will be similar to the technical analyses for the compliance period. The primary difference will be in the metrics used to evaluate the results of the analyses. Figure 6-1 provides the framework for the minimization process used for the protective assurance analyses applied to 10 CFR 61.41(b). The recommended approach is to treat the minimization process similar to an optimization problem, using the doses estimated from the technical analyses (e.g., performance assessment, intruder assessment) as the objective function. The requirements for protective assurance analyses apply to both 10 CFR 61.41(b) and 10 CFR 61.42(b), however, the process for the latter should be simpler.

Figure 6-1 depicts levels that licensees should consider and regulators should evaluate that distinguish different degrees of effort and types of analyses that may be performed for the minimization process. A graded approach to the protective assurance period analyses is recommended. Licensees should consider uncertainty in the protective assurance analyses. The absence of the evidence of risk does not prove that risks are not present. For example, a licensee may claim that no releases from their LLW disposal facility have been observed, however, they may not have installed any monitoring wells that would be able to detect such releases (i.e., the absence of the evidence of risk). This claim would have significantly different meaning than the assertion by a licensee that releases from their LLW disposal facility have not been observed because monitoring wells were installed and samples were tested (i.e., evidence that risks are not present).

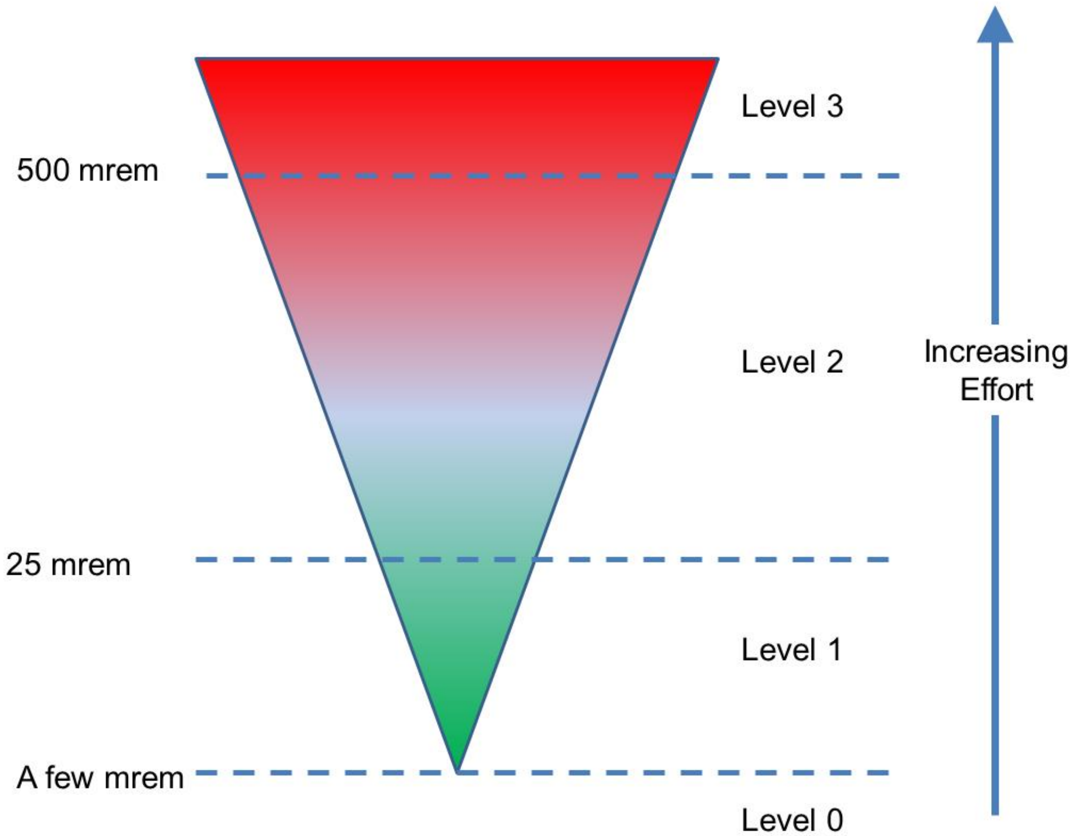

Figure 6-1 Analyses Framework for the Minimization Process for the Protective Assurance Period Analyses Applied to 10 CFR 61.41(b)

Proposed waste disposal is different from a remediation or clean-up activity in that waste disposal is a potential *future* action that could result in future harm to the public, whereas a remediation activity involves evaluating what should be done to remedy a *previous* action that could result in future harm to the public. The operator of a waste disposal facility can set waste concentration and inventory limits that will control future doses to essentially any level desirable if the associated technical analysis is of high quality and is reasonably accurate. Inventory limits are quantity- or concentration-based limits on the amount of radioactive isotopes suitable for disposal at a particular location. Inventory limits can play a key role in managing risk.

Uncertainty in projected doses is an important factor for licensees and regulators to consider when determining the appropriate target to use when evaluating the minimization process. If there are significant uncertainties, then the minimization process should be biased towards more conservative levels (i.e., more effort to minimize). The levels a licensee may consider for minimization under 10 CFR 61.41(b) include:

Level 0: At hundredths of mSv/yr (a few mrem/yr and below), design, process, waste acceptance, or other changes are generally not warranted unless they result in a cost savings without increasing worker exposures. Therefore, analyses of alternatives are not necessary for Level 0.

<u>Level 1</u>: Above a few mrem/yr and up to the compliance period dose limit of 0.25 mSv/yr (25 mrem/yr), changes to design, process, waste acceptance or other areas may be warranted if they can be justified based on technological and economic considerations. The analyses of alternatives may be qualitative or quantitative. Quantitative analyses are preferred. Inventory limits may be used to limit doses if there is uncertainty that the doses are Level 1 or that they may be higher. A licensee may also propose and implement inventory limits for purposes other than the quantitative dose assessment (e.g., to simplify waste handling and management).

<u>Level 2</u>: Above 0.25 mSv/yr (25 mrem/yr) and up to 5 mSv/yr (500 mrem/yr), changes to design, process, waste acceptance or other areas may be warranted unless they are shown to be impractical based on technological and economic considerations. The analyses of alternatives should be quantitative to the extent practical. Inventory limits should be used to maintain projected future doses below 5 mSv/yr (500 mrem/yr) and those inventory limits should be reflected in the associated waste acceptance criteria.

<u>Level 3</u>: Above 5 mSv/yr (500 mrem/yr), changes to design, process, waste acceptance, or other areas are expected of the licensee unless they are shown to be impractical based on technological and economic considerations. For example, changes to the wasteform or geochemistry of the disposal cells may significantly reduce projected future doses. The analyses of alternatives should be quantitative, and include a rationale for why the annual dose cannot be reduced to 5 mSv/yr (500 mrem/yr) based on technological and economic considerations. The analyses of alternatives should consider why inventory limits cannot be established. The licensee and regulator should consider if an alternative facility could receive the waste and maintain doses below 5 mSv/yr (500 mrem/yr).

For Level 3, the analyses of alternatives should be broader and more comprehensive compared to the other levels. One method that is irrefutably capable of reducing risk is to establish concentration- or quantity-based inventory limits. Inventory limits may be used to account for potential shortcomings in the engineered or natural components of a LLW disposal system. In addition, if the results of the analyses demonstrate that doses for 10 CFR 61.41(b) are likely to be above 5 mSv/yr (500 mrem/yr), the results may indicate that the proposed disposal facility and disposal site are not suitable candidates for that type of waste. Alternative disposal facilities may exist that can better manage the particular radiological hazard.

The minimization process for 10 CFR 61.42(b) is conceptually similar to 10 CFR 61.41(b) with the exceptions that different levels and a simpler process can be used. A variety of factors contribute to this recommendation. The inadvertent intruder is a hypothetical construct to account for the uncertainty with respect to providing long-term control of a closed disposal site, and intruder doses are usually driven by short-lived waste for most commercial LLW. In addition, the dose limit for the intruders during the compliance period is significantly higher than the limit found in 10 CFR 61.41(a). Finally, the long-term performance of engineered barriers to inhibit intruder doses during the protective assurance period cannot be reliably assured. Each of these factors contributes to making the minimization process for the intruders somewhat different than for 10 CFR 61.41(b). Whereas there may be practical actions that can be taken to minimize doses to a member of the public for 10 CFR 61.41(b), it is more challenging to identify actions to minimize doses for a hypothetical intruder scenario. Because it is more difficult to identify actions, a simpler approach is recommended for minimizing intruder doses. The recommended approach for 10 CFR 61.42(b) is to minimize intruder doses below a 500 mrem/yr target (analogous to Level 1 above but with the corresponding equivalent threshold) or to a level that can be justified based on technological and economic considerations.

6.2.1 Types of Analyses

A licensee has flexibility in the type of analyses to use for the protective assurance period. The analyses should be tailored to the specific waste, disposal facility design, and the projected future radiological doses. The suitability of particular analyses to support decision-making may be impacted by projected uncertainty. If projected uncertainty is relatively large, it may not be clear from the results of analyses which alternatives should be adopted and which can be rejected. Therefore, the licensee should err on the side of evaluating more alternatives to ensure defense-in-depth will be provided. In addition, a larger set of alternatives may be considered because some of those alternatives may help to reduce uncertainty in the projected performance.

6.2.1.1 *Alternatives Analyses*

The simplest form of analysis for the protective assurance period is for a licensee to compare alternatives. This section provides guidance on:

What alternatives should be considered by a licensee?
How much detail should be included in the analyses?
Should combinations be evaluated by a licensee?

In general, in an alternatives analysis, a licensee will have a base case or preferred alternative with an associated projected impact (i.e., dose). An alternatives analysis can be simpler than a minimization or cost-benefit analysis because economic variables may be omitted. For the alternatives analysis, the base case or preferred alternative should be the alternative that is projected to result in the lowest dose or that calculates a dose comparable to the lowest result given the uncertainty. If the preferred alternative dose is not comparable to the lowest dose, then technological and economic practicality can be factored into the decision, as discussed in Section 6.2.1.2.

Performance assessments may be deterministic or probabilistic, but regardless of the type of analyses all performance assessments should consider uncertainties. The base case or preferred alternative will usually have the lowest projected doses. However in some cases a number of alternatives may be comparable when uncertainties in the projected doses are considered. The projected uncertainties will be reflected in a range of estimated doses. If the analysis is probabilistic, the appropriate metric to use is the peak-of-the-mean dose. Though the peak-of-the-mean dose is a scalar output, it will have uncertainty associated with the estimated value. The uncertainty in the estimates of the peak-of-the-mean doses for different alternatives may overlap. Alternatively, plots of other percentiles of projected doses can be compared when selecting an alternative. When uncertainty causes the results to overlap the "lowest" result may not be unambiguously identified, and therefore other considerations may be taken into consideration when selecting the preferred alternative or base case.

The main variables to consider as alternatives generally include:

- Design (e.g., different engineered barriers),
- Processing (e.g., waste emplacement and configuration), and
- Waste acceptance (e.g., waste types, waste streams, waste characteristics).

The framework for the protective assurance period analyses provides for a risk-informed approach based on the projected future doses. For projected future doses of a few mrem per year and less (Level 0), formal evaluation of alternatives is not necessary. Because the doses are low, essentially the case for minimization has already been established by the licensee in the base case or preferred alternative. An exception would be if the projected dose is low but the uncertainty is high. In this case, it may be reasonable to evaluate alternatives to the base case to see if the uncertainty can be reduced or managed. It should be noted that reduction in uncertainty may not result in a reduction of risk; rather the risks may be better understood.

For projected future doses greater than a few mrem per year and up to 0.25 milliSieverts per year (25 mrem per year) (Level 1), an evaluation of alternatives is recommended. However, that evaluation should be focused on first-order effects of the main variables (e.g., design, processing, waste acceptance). A large number of alternatives do not need to be considered; generally less than ten alternatives should suffice. The analyses may be qualitative, although quantitative analyses are preferred. The experience base considered for design and process changes should include domestic experience, though licensees may also consider international experience.

For projected future doses greater than 0.25 mSv/yr (25 mrem/yr) and up to 5 mSv/yr (500 mrem/yr) (Level 2), an evaluation of alternatives is recommended. Changes to design, process, waste acceptance or other areas may be warranted unless their adoption cannot be justified based on technological and economic considerations. The alternatives analysis should be quantitative to the extent practical. The experience base considered for design and process changes should focus on domestic experience but may also include international experience. The number of alternatives considered should be complete without being exhaustive. For example, the licensee should be able to use the results of the performance assessment to identify those features of the design that are most important to limiting releases, or that provide defense-in-depth. Alternatives analyses should include variants of the key design features. Design alternatives should include those related to the hydrology, geochemistry, site stability, wasteforms, or other significant characteristics. Depending of the projected doses, a licensee may wish to consider combinations of alternatives, as the projected responses of performance assessment models is not always linear and complex responses can occur. Alternatives may be rejected if they are not technologically or economically practical irrespective of the benefits to system performance.

A primary difference between the analyses for Level 2 and Level 1 is the consideration of inventory limits to maintain projected future doses to a prescribed level.[1] Inventory limits should

[1] This section is focused on 10 CFR 61.41(b). As noted previously, the approach recommended for 10 CFR 61.42(b) is simpler.

be used to maintain projected future doses below 5 mSv (500 mrem) and those inventory limits should be reflected in the associated waste acceptance criteria. For waste disposal, inventory limits can be derived that correspond to different levels of dose to a member of the public. In many cases, it may be practical for a licensee to set inventory limits that correspond to a fraction of the 5 mSv (500 mrem/yr) target. A licensee should consider alternative inventory limits in the minimization process for Level 2.

For projected future doses to a member of the public greater than 5 mSv/yr (500 mrem/yr) (Level 3), evaluation of alternatives is necessary. The licensee is expected to make changes to the design, process, waste acceptance or other areas unless changes cannot be justified based on technological and economic considerations. The experience base considered should include domestic and international experience as well as emerging technologies that may become viable in the near term. The number of alternatives the licensee considers should be complete and include the identification of relevant combinations of alternatives that may have significantly increased performance. Design features that act in combination may enhance performance or provide defense-in-depth. The analyses of alternatives performed by a licensee should be quantitative, and include a rationale for why the annual dose cannot be reduced to 5 mSv (500 mrem) or lower based on technological and economic considerations. The licensee should justify in the alternatives analysis why inventory limits cannot be established to lower the projected future dose. The presence of previous disposals that could result in future doses greater than 5 mSv (500 mrem) is not a sufficient basis for allowing future LLW disposals to result in doses of that magnitude. Previous and future disposals may be managed separately such that the impacts do not overlap, especially with respect to demonstration of compliance with 10 CFR 61.42(b). The licensee should provide the regulator with a strong basis for why the waste should be accepted at their facility, despite the higher projected dose, as opposed to being disposed at an alternate LLW disposal facility. The regulator should consider, through consultation with peers at other regulatory agencies, if an alternative facility could receive the waste and maintain doses below 5 mSv (500 mrem). The alternative facilities considered should be limited to existing facilities or proposed facilities for which technical analyses are available. In most cases existing facilities will have developed inventory limits for a large number of isotopes. Therefore, it should be easy to determine the quantity of a particular new waste stream that an existing facility could suitably dispose.

6.2.1.2 *Minimization Analysis*

Whereas the alternatives analysis discussed in the previous section examines different options based on projected annual doses, the minimization analysis may also include economic considerations. This section provides guidance for licensees completing analyses and for regulators reviewing analyses on:

- Long-term discounting,
- Metrics to use for minimization analysis, and
- Consideration of uncertainty.

A challenge with minimizing the long-term impacts from LLW disposal is that the costs may be incurred in the near term, whereas the impacts or benefits, such as averted doses, may not be observed until hundreds or thousands of years in the future. In addition, the size of the group that may be exposed in the future, especially the distant future, is difficult to estimate with a high degree of confidence due to the complexity of estimating future land use and demographic changes. There is no clear consensus in the technical literature with respect to discounting very long-term impacts in order to perform cost-benefit analysis or other similar types of analyses. Discounting has been applied by some researchers, though the timeframes are generally limited to a few hundred years. Some researchers have inferred effective discount rates from financial data (e.g., long-term lease data) and have concluded that they are likely to be very low (e.g., fractions of a percent) with respect to financial decisions (Giglio et al., 2013). The issue of *long-term* discounting combines technical and philosophical components; staff favors a pragmatic solution over theoretical rigor.

The NRCs recommended approach to discounting applied to regulatory analysis development for backfitting can be found in NUREG/BR-0058, Rev. 4 (NRC, 2004d).[2] A distinction is made between shorter-term problems (e.g., reactor licensing) and problems involving the long-term and potential intergenerational considerations (e.g., decommissioning or waste disposal).

The approach recommended here (e.g., long time horizons) has four components:

1. Discount costs of alternatives over the operational life,
2. Do not discount long-term future averted doses (i.e., benefits), and
3. Evaluate alternatives based on a) the normalized effectiveness of the alternative and b) the absolute level of the risk involved.
4. Consider uncertainty and sensitivity in the assumptions.

Discounting of costs to compare design alternatives is a well-established method used in engineering economics. Consideration of the time value of money is central to most engineering projects. For example, to compare two alternatives one that involves a capital expenditure today with one that involves an expenditure that will occur *n* years in the future, the present value of the future expenditure is estimated with:

$$PV = FV \frac{1}{(1+r)^n}$$

where r is the annual discount rate.

[2] The NRC staff's recommended approach to discounting for shorter-term problems was initially reflected in NUREG-1757, Appendix N for application to ALARA analyses in decommissioning (up to a 1,000 year timeframe). However, portions of that appendix, including the recommendations for discounting, were later withdrawn (NRC, 2007d). NUREG/BR-0058, Rev 4 discusses the issue: For certain regulatory actions, such as those involving decommissioning and waste disposal issues, the regulatory analysis may have to consider consequences that can occur over hundreds, or even thousands, of years. The Office of Management and Budget (OMB) recognizes that special considerations arise when comparing benefits and costs across generations. Under these circumstances, OMB continues to see value in applying discount rates of 3 and 7 percent. However, ethical and technical arguments can also support the use of lower discount rates. Thus, if a rule will have important intergenerational consequences, one should consider supplementing the analysis with an explicit discussion of the intergenerational concerns such as how future generations will be affected by the regulatory decision. Additionally, supplemental information could include a presentation of the values and impacts at the time in which they are incurred with no present worth conversion. In this case, no calculation of the resulting net value or value-impact ratio should be made. Also, one should consider a sensitivity analysis using a lower, but positive discount rate. Finally, as a general principle, sensitivity or uncertainty analysis, or both, should be performed.

On the other hand, discounting of benefits (e.g., averted doses) is open to considerable debate. Over very long timeframes, the mathematics of discounting results in the conclusion that the current generation should not invest any resources to mitigate impacts that occur to distant future generations. The NRC staff's recommendation not to discount long-term, future averted doses is based on the position that the current generation is responsible for the long-term impacts from its LLW disposal decisions and that the solution for these impacts should not be deferred to future generations.

In order to compare alternatives, the recommended approach is 1) to normalize the cost of the alternative to what is considered to be an appropriate amount (cost) to protect the current generation (e.g., the base cost of the facility), and 2) to scale the normalized result based on risk. Higher risk should result in a higher threshold to reject an alternative, whereas at very low risk, all alternatives should be rejected. The use of the term 'risk' here is referring to the projected doses to a member of the public or an inadvertent intruder. A broader interpretation of risk for the risk-based discounting process may unnecessarily complicate the decision-making process. However, licensees may choose to consider the balance between future risk from disposed waste and present risk to workers or the public. For example, a wasteform with much higher durability could have much lower waste loading, resulting in a transferal of risk but not a significant reduction (e.g., from disposal to transportation). The metric the NRC staff developed is to compare the proportional increase in cost for the alternative relative to the base cost of the facility (e.g., the appropriate cost to protect the current generation) against the fractional change in long-term impacts. The overall result is then conditional on the absolute level of the risk as presented in Figure 6-1. This is explained in more detail with an example later in this section.

<u>Long-term Discounting:</u>
The NRC has developed a policy to inform regulatory decision-making with respect to rulemaking that is subject to NRC's backfit requirements. A $2,000 per person-rem conversion factor has been applied to inform regulatory decisions for fuel cycle facilities (NUREG-1530) and evaluate potential new regulatory requirements (NRC, 1995d; NRC, 2004d). The conversion factor is also used in regulatory applications, such as in ALARA analyses, to provide a monetary valuation to collective dose. A number of criticisms have been expressed about the use of collective dose (NCRP, 1995). Though some have found collective dose still has value in comparing alternatives (Brock and Sherbini, 2012). The dollar per person-rem conversion factor attempts to capture the dollar value of the health detriment resulting from radiation exposure. Health detriments (e.g., excess cancer fatalities) are linked to radiation exposure through conversion factors (e.g., 0.05/Sv).

In NUREG-1530, the NRC staff evaluated different methods to value a statistical life to develop a dollar per person-rem factor (NRC, 1995d). One method looked at values implied by government expenditures for many different programs designed to protect human life. The values in 1990 dollars ranged from $12,000 per statistical life for scoliosis and neuromuscular disease to $85,000 for regulatory and warning signs. The implied value to limit exposure in the defense HLW program was $490 million per statistical life. The primary driver of the large range of results was the differences in the amount spent on each program, not in the methods to calculate the statistical deaths. The NRC staff's evaluation resulted in a large range of values of expenditures per statistical life and the values for nuclear issues, especially nuclear waste issues, tended to be at the very high end of the range.

The range of positions taken on long-term discounting is extremely large (Farber and Hemmersbaugh, 1993). There are a variety of considerations discussed in the technical literature that the NRC staff considered when developing this guidance. These include but are not limited to:

- The long-term doses from LLW disposal could be relatively small but persist for a very long period of time. Without discounting, the cumulative effect could be very large if the exposed population is large. However, the incremental increase in risk to any individual would be very small, perhaps below the threshold where individuals take action or otherwise modify their behaviors.
- Because of the timeframes involved, if a licensee were to use discounting to estimate the present worth of benefits (e.g., averted doses), even at very low discount rates, the licensee may conclude that no amount should be spent today to mitigate long-term radiological risks (i.e., beyond a few hundred years).
- Society incurs the cost of LLW disposal regulation long before the benefits of doses averted; compound discounting has a greater impact in the calculation of the present value of benefits than on the costs because the benefits occur over much longer timeframes.[3]
- Most studies of discounting are focused on the impacts within a generation and not on the impacts to later generations. Studies that have looked at longer timeframes have generally been limited to around a hundred years because there are not many longer term problems.
- The NRC staff acknowledges that discounting is based on unstated economic assumptions that may not be valid over very long timeframes (NRC, 1982b).
- Temporal volatility in discount rates can increase future valuations significantly compared to assuming that rates are constant (Newell and Pizer, 2003).

Consistent with guidance provided in NUREG-1854 (NRC, 2007a), future long-term doses should not be discounted with time to present day values in order to compare alternatives.[4] As discussed below, the recommended approach for a licensee to use is to compare the long-term costs and reductions in dose to the compliance period costs and effectiveness of the design while scaling the result with the magnitude of the projected long-term impacts. In other words, even for a large reduction in long-term doses if the baseline long-term doses are small, the resource expenditure is likely not warranted. This approach could be described as a normalized utility-based approach with a floor threshold. The recommended approach is based on

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[3] Although a present benefit from disposal would be that the public is not exposed to radiation if the waste is disposed compared to a scenario if the waste is not disposed and control is lost.

[4] Some stakeholders have referred to Appendix N of NUREG-1757 as providing guidance on the topic of long-term discount rates. However, relevant portions of Appendix N were withdrawn after issuance and are yet to be revised. This guidance refers to NUREG/BR-0058, Rev. 4, "Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission" (NRC, 2004d). Section 4.3.5 of NUREG/BR-0058 indicates that for certain regulatory actions, such as those involving decommissioning and waste disposal, special considerations arise when considering benefits and costs across generations. Section 4.3.5 indicates that the analysis should be supplemented with an explicit discussion of intergenerational concerns. This could be done by performing the analysis based on costs and impacts at the time they are incurred, with no present worth conversion, or by performing a sensitivity analysis using lower discount rates.

individual doses, thus avoiding the issues noted above with use of collective dose and cumulative impacts.

The recommended approach is to estimate the cost of the alternatives represented by current net present value (NPV) by applying discounting over the projected operational period of the facility. A range of discount rates should be considered, such as in the range of 1 to 7 percent, but biased towards the long-term trend values. Though long periods of deflationary rates have not been frequent historically, the licensee could consider the sensitivity of the NPV calculations to a deflationary period or periods. Sensitivity of the NPVs to the uncertainty in discount rates should be examined. Considering the uncertainty, a licensee should be biased towards conservatism (i.e., select alternatives that provide a greater reduction in risk). After the operational period and preparation for closure, the site operator is not expected to be performing significant activities at the disposal facility; therefore, discounting should not apply after the operational period.

Metrics to Use for Minimization Analysis:
The performance metrics a licensee must apply to the assessment of long-term releases during the protective assurance period is to minimize releases (10 CFR 61.41(b)) and to minimize exposures to any inadvertent intruder (10 CFR 61.42(b)). In addition, the licensee must demonstrate stability of the disposal site after closure (10 CFR 61.44). A target to compare this minimization against is provided in the regulation (i.e., 5 mSv (500 mrem), or to a level that is supported as reasonably achievable based on technological and economic considerations). The metrics afford flexibility to a licensee to consider socioeconomic factors when assessing the long-term protection of public health and safety.

These requirements to minimize releases and exposures are intended to be conceptually similar to aspects of the ALARA requirement[5] found in 10 CFR Part 20, which includes the use of optimization, feasibility analyses, and traditional cost-benefit analyses. The 5 mSv (500 mrem) value provided in the regulation is a target or dose goal to use in the minimization process. It is not identical to a dose limit. In most cases, the NRC staff expects that the minimization process will produce a design that is projected to result in doses to a member of the public much lower than the target value. The minimization analysis is conceptually similar to ALARA, but it is not identical.

Because of the problems associated with discounting over long timeframes, the NRC staff recommends that licensees follow the process given below to implement the minimization process. Other processes may also be suitable and regulators may evaluate any other processes on a case-by-case basis. Based on the results of their minimization analyses, licensees may elect to adopt alternatives that are more protective.

The analyses should be based on best estimates and uncertainties. Uncertainty may impact whether an alternative should be adopted or not. If the uncertainties are low, and confidence in the decision to eliminate an alternative is high, then it is practical to not adopt the alternative. If

[5] ALARA is defined as "making every reasonable effort to maintain exposures to radiation as far below the dose limits in this part as is practical consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to the state of technology, the economics of improvement in relation to benefits to public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest." See 10 CFR 20.1003.

the uncertainties in the estimates are comparatively higher, and confidence in a decision to eliminate an alternative is low, then caution is warranted and the alternative should be adopted. If the uncertainties are prohibitively large (see Section 6.2.1.4), then inventory limits may be necessary to mitigate those uncertainties or disposal of certain waste isotopes may be not be appropriate. Because of the different types of uncertainties and their magnitudes in relation to the decision metrics, many different approaches to factoring uncertainty into the minimization process may be appropriate and should be evaluated on a case-by-case basis. A licensee is not required to, but may consider, performing the minimization process calculations probabilistically. Uncertainty in the doses, net present values, design effectiveness, and level scaling factors could be included resulting in probability distributions of the outputs.

Minimization Process:
The following variables are defined:

"D_x" is a dose for scenario or alternative x in units of mrem/yr
"NPV_x" is the net present value for scenario or alternative x in units of $
"Eff_x" is the effectiveness of the scenario or alternative x in units of mrem/yr-$

$\boldsymbol{D_{base}}$ = Peak dose from the base design within the protective assurance period
$\boldsymbol{D_{natural}}$ = Peak dose without the base design within the protective assurance period (natural barrier capabilities only)
$\boldsymbol{D_{natural\text{-}int}}$ = Peak dose to the intruder without the base design during the protective assurance period
$\boldsymbol{D_{base\text{-}int}}$ = Peak dose to the intruder with the base design during the protective assurance period
$\boldsymbol{NPV_{base}}$ = NPV of the base design ($)
$\boldsymbol{Eff_{base}}$ = the effectiveness of the base design within 10,000 years (dose/$)
$\boldsymbol{D_{alti}}$ = Peak dose from alternative i during the protective assurance period
$\boldsymbol{NPV_{alti}}$ = NPV of alternative i ($)
$\boldsymbol{Eff_i}$ = the effectiveness of alternative i for the protective assurance period (dose/$)
Lf = Level scaling factor[6] (dimensionless)
NER = Normalized Effectiveness Ratio

For evaluation of minimization with respect to 10 CFR 61.41:

For Dbase < 25 mrem/year: Lf = 0
*For Dbase >= 25 mrem/year: Lf = 0.13 * (DBase)* $^{0.333}$

For evaluation of minimization with respect to 10 CFR 61.42:

For $Dbase_{-int}$ *< 500 mrem/year: Lf = 0*
For $Dbase_{-int}$ *>= 500 mrem/year: Lf = 0.13 ** $(Dbase_{-int})^{0.333}$

1) Calculate the effectiveness of the base design using:

$$Eff_{base} = \frac{Dnatural - Dbase}{NPVbase} \qquad (6.1)$$

[6] Development of the expressions for the level scaling factors is discussed later in this section.

2) Calculate the effectiveness of the n protective assurance period alternatives (for i = 1 to n) using:

$$Eff_i = \frac{Dbase \ \ -Dalt_i}{NPValt_i} \quad (6.2)$$

3) Compare the results with the expression*:*

$$NER_i = \frac{DEBase}{DEi} > Lf \quad (6.3)$$

If NER_i is greater than *Lf* for all alternatives, then the alternatives are not viable (i.e., minimization has been achieved). Example 6.1 demonstrates the application of this approach.

The peak doses used in the minimization process analysis should be consistent with the type of analyses performed for the performance and intruder assessments. For instance, if probabilistic analysis is used the recommended metric is the peak-of-the-mean. Uncertainty in the magnitude and timing of the peak doses should be considered, especially if deterministic analyses are used.

Figure 6-2 provides a conceptual representation of the level scaling factor (*Lf*), which is used to compare with the normalized effectiveness ratio (*NER*). The value of the constant and the exponent in the following equation ($Lf = 0.13 * (Dbase, Dbase_{-int,} Dnatural,$ or $Dnatural_{-int,})^{0.333}$) were selected to ensure the following:

- At very low values of dose, no resources would be expended to further reduce the doses,
- At a dose of 500 mrem during the protective assurance period, the effectiveness of an alternative would be compared on an equal basis with the effectiveness of the base design during the compliance period, and
- At doses greater than 500 mrem, more resources would be practical to apply to reduce the potentially large impacts.

The use of the level scaling factor, *Lf,* is a risk-based discounting approach. Figure 6-3 provides the various *Lf* values highlighted on a hypothetical performance assessment model output that would be used to demonstrate minimization for 10 CFR 61.41(b).

The benefits of this approach are 1) strong base designs are encouraged (i.e., larger Eff_{base}), 2) costs are scaled with doses, 3) resources are not expended for reducing very low doses, and 4) transparency of costs and alternatives is provided to regulators and other stakeholders. Summary points of the approach are:

- It is a benefit to maximize Eff_{base}, This can be done by implementing as effective a design as possible in a cost-effective manner (i.e., maximize performance, minimize cost).
- It is also a benefit to having a highly-effective natural system (i.e., high-performance LLW disposal site), because the *Lf* is scaled with overall dose levels.
- It is a benefit to minimize *Dbase*. Selecting a base design that performs well for the protective assurance period will reduce the viability of alternatives.

Example 6.1: A license applicant has developed an application to dispose of commercial LLW at the Nerak Site. If approved, the waste will contain a mixture of short- and long-lived isotopes. The applicant performed analyses of their base case design and estimated the peak dose to be 5 mrem/yr within 1,000 years and 172 mrem/yr within 10,000 years. They then performed analyses of the waste in the disposal site without the benefit of the base design features (e.g., engineered cover, concrete vaults, and waste packages) and estimated the peak dose would be approximately 220 mrem/yr at 10,000 years. The applicant's estimates of costs and doses are based on the median results of probabilistic analyses. The applicant considered three alternatives to the design and evaluated the effectiveness of those alternatives in minimizing projected doses for the protective assurance period. The results of various analyses developed by the applicant are:

Description	**Time (yr)**	**NPV Cost ($)**	**Peak dose (mrem/yr)**
Base case – compliance	1,000	10,000,000	5
Site effectiveness –	10,000	NA	220
Base case – protective assurance	8,437	30,000,000	172
Alternative 1 – improved wasteform	10,000	110,000,000*	15
Alternative 2 – improved cover	8,708	20,000,000*	137
Alternative 3 – chemical barrier	10,000	1,000,000*	69

* Increase in cost over the base case, NPV = net present value

$$Eff_{base} = \frac{(220 - 172)mrem/yr}{\$30{,}000{,}000} = 1.6\text{E-}6\ \frac{mrem}{\$\text{-yr}}$$

$$Eff_1 = \frac{(172 - 15)mrem/yr}{\$110{,}000{,}000} = 1.42\text{E-}6\ \frac{mrem}{\$\text{-yr}}$$

$$Eff_2 = \frac{(172 - 137)mrem/yr}{\$20{,}000{,}000} = 1.75\text{E-}6\ \frac{mrem}{\$\text{-yr}}$$

$$Eff_3 = \frac{(172 - 69)mrem/yr}{\$1{,}000{,}000} = 1.03\text{E-}4\ \frac{mrem}{\$\text{-yr}}$$

$$Lf = 0.13 * (172)^{0.333} = 0.72$$

NER_1 = 1.13, NER_2 = 0.91, and NER_3 = 0.02. Since NER_3 is less than the L_f, then the base design does not adequately minimize releases (in the case of releases to the general population). The exposures to inadvertent intruders would be evaluated with a similar approach using the pertinent information. The license applicant proposes in their application that a chemical barrier will be added to the base case design in order to minimize releases for the protective assurance period.

Conclusion: After examining the sensitivity of the results to the uncertainties, the regulator concludes that with the chemical barrier added (Alternative 3) the license applicant has demonstrated that releases would be minimized for the protective assurance period.

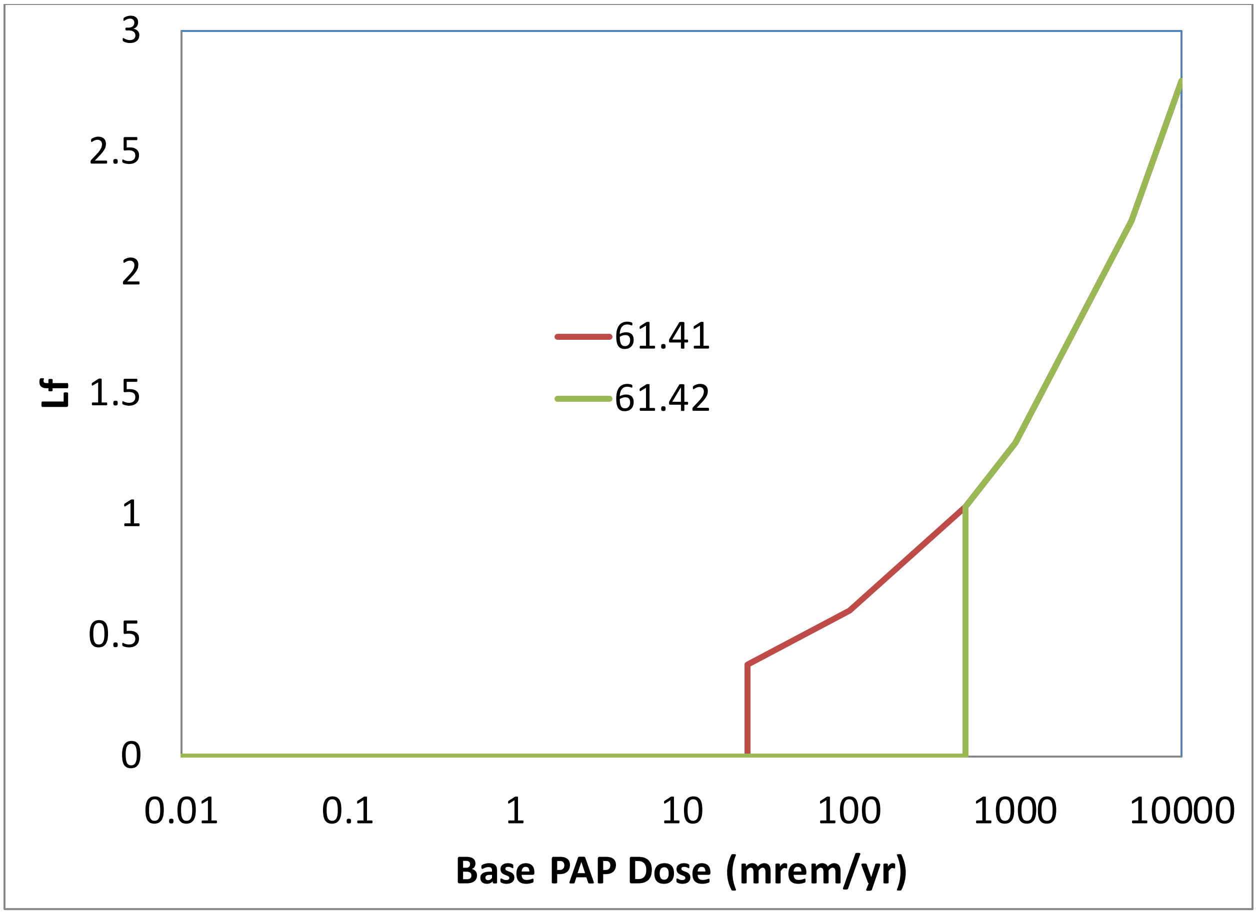

Figure 6-2 Level Scaling Factors as a Function of the Base Case Dose in the Protective Assurance Period (For 10 CFR 61.41 and 10 CFR 61.42)

- By setting the *Lf* to 0 below a threshold, design alternatives will not be implemented, and therefore, costs will not be incurred by current generations to reduce doses that are already low from a holistic risk perspective.
- Inventory limits can be used to avoid costs associated with implementing alternatives to reduce large doses that may be incurred from a large radionuclide inventory.

In addition to the quantitative information discussed above, the licensee may provide regulators with the proportion of resources that they propose to use to achieve the protection of public health and the environment for different timeframes. This information can help identify disproportionate costs and benefits in the proposed approach, and provide transparency to stakeholders. It can also help communicate the proposed approach in terms of the commitment to short- and long-term environmental protection. These resource estimates should only be discounted up to the closure of the facility, as no long-term design changes are expected to be implemented following closure.

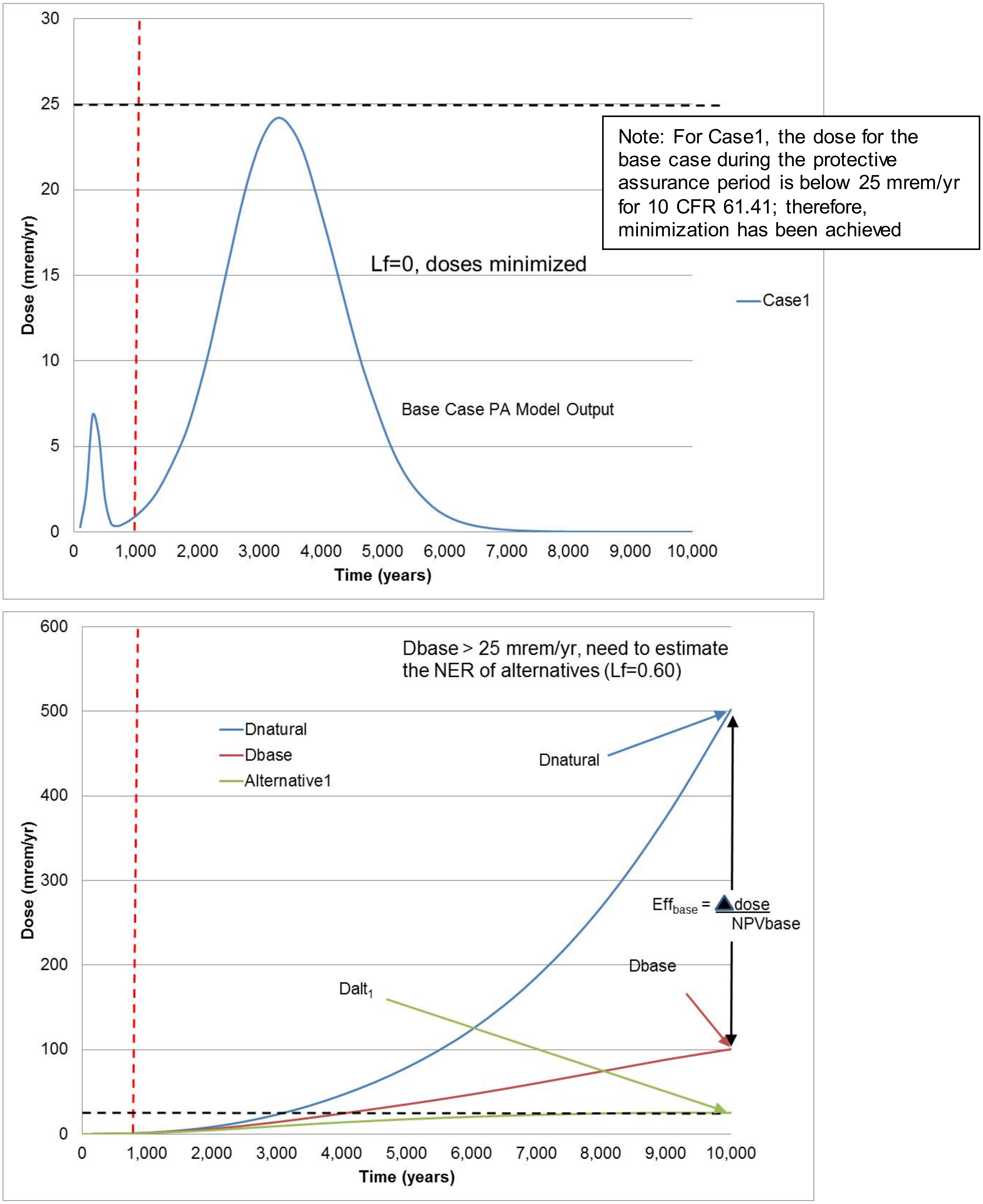

Figure 6-3 Hypothetical Performance Assessment Model Output with the Minimization Parameters

The alternatives evaluated under the minimization process should be limited to those that are currently technically feasible. It is not necessary to attempt to project the development of future practices. The cost estimates should reflect the uncertainties associated with the maturity of the technology by considering different ranges of effectiveness for a unit cost or a range of costs for a given effectiveness.

6.2.1.3 *Other Decision Analyses*

Other decision analyses techniques may be applied by licensees and regulators should review each type of analyses on a case-by-case basis. For instance, cost-benefit analyses are used to evaluate alternatives and facilitate decision-making. NRC has developed guidance for cost-benefit analyses applied to environmental reviews (NRC, 2003d, Section 6.7) and waste incidental to reprocessing waste determinations (NRC, 2007a). However, direct application of cost-benefit analyses to the very long timeframes associated with LLW disposal is tenuous because discounting can be difficult, as well as accurately estimating the population surrounding a disposal site thousands of years into the future. In previous staff guidance, NRC has recommended that the monetary value associated with averted future doses should not be discounted in the analyses for application to 10 CFR Part 61 (NRC, 2000c).

6.2.1.4 *Other Considerations*

According to 10 CFR 61.50(a)(1), to the extent practicable, the disposal site shall be capable of being characterized, modeled, analyzed, and monitored. In addition, a licensee must account for uncertainty and variability in the performance assessment analyses. Over the protective assurance period, stability of the disposal site may be difficult to demonstrate if the disposal site is in an unfavorable location. In some circumstances, a licensee may not be able to adequately reflect uncertainties in the long-term technical analyses. In these cases, the licensee or regulator should impose inventory limits as a method to manage the uncertainties that may not be adequately assessed with technical analyses. Example 6.2 provides information on how other considerations can be used to ensure protection of public health and safety during the protective assurance period.

Example 6.2

The Radala disposal site is located in a semi-arid environment with a relatively stable present day environment. A license applicant proposes to dispose of a waste stream comprised of large quantities of long-lived waste in the disposal facility. The projected future environment is anticipated to be unstable due to geomorphological processes (e.g., high erosion associated with landform evolution). The performance assessment from the compliance period is used to estimate potential future doses during the protective assurance period. Projected doses to a member of the public are estimated to be approximately 100 mrem/yr. The regulator reviews the analyses and determines that the licensee did not adequately incorporate the uncertainty in erosion rates driven by variability in future climate states. If uncertainty in erosion rates is considered, the projected future doses can be on the order of many thousands of mrem per year. In response to a request from the regulator, the license applicant evaluates different design alternatives and determines that none can be relied upon to significantly reduce the projected future doses or that the alternatives would be prohibitively expensive.

Conclusion: The regulator approves of the application with conditions. The disposal of either limited quantities or concentrations of the waste stream is approved. The regulator agrees with the licensee that no technologically or economically practical alternatives exist to prevent disturbance of the disposal facility by the geomorphological processes. The regulator examined other operating LLW disposal facilities and determined that other facilities have been analyzed for disposal of the waste stream. Other facilities, due to favorable site conditions for long-lived waste disposal, could dispose of the waste stream and are projected to result in a radiation dose to a member of the public of a few mrem per year. Considering the uncertainty and the fact that the license applicant cannot demonstrate long-term stability of the disposal site, the regulator determines that inventory limits should be developed. The regulator provides inventory limits as a license condition that limit the inventory to a fraction of the inventory originally proposed by the licensee. The licensee can determine whether it is economically viable to dispose of the waste stream at the inventory limits.

7.0 PERFORMANCE PERIOD ANALYSES

10 CFR 61.13(e) requires performance period analyses to:

(1) Assess how the disposal facility and site characteristics limit the potential long-term radiological impacts, consistent with available data and current scientific understanding.

(2) Identify and describe the features of the design and site characteristics that will demonstrate that the performance objectives set forth in 10 CFR 61.41(c) and 10 CFR 61.42(c) will be met.

The primary purpose of the performance period analyses is to provide information that demonstrates that releases of long-lived[1] radioactive waste from a disposal facility are minimized to the extent reasonably achievable. The protective assurance period is defined in the regulations as the period from the end of the compliance period through 10,000 years following closure of the site. The performance period is defined in the regulations to be the period of time following the protective assurance period. Performance period analyses are required only if the disposal facility is accepting long-lived waste that has disposal site-averaged concentrations of long-lived radionuclides greater than the values provided in Table A of 10 CFR 61.13(e), or if necessitated by site-specific conditions. Table 7-1 lists long-lived isotopes that may be present in LLW inventories.

The disposal system consists of the disposal units, disposal site, land disposal facility, and surrounding environment. The assessment should evaluate natural and engineered characteristics of the disposal system and describe how those characteristics will reduce long-term impacts. Over the long timeframes of regulatory concern, performance of the disposal system is likely to be driven by the features of the natural system rather than by man-made engineered barriers. The level of detail in the assessment should be risk-informed. The licensee should calculate the expected concentrations of long-lived waste remaining in the disposal site after the protective assurance period to risk-inform the longer-term performance period analyses. In general, the amount of resources and effort devoted to the assessment for the performance period will increase in proportion to the magnitude of the longer-lived radioactive waste inventory, considering both the initial inventory and ingrowth. Table 7-2 provides examples of how performance period analyses may be risk-informed, taking into account the longevity of the inventory and the duration of the hazard it poses.

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[1] Long-lived waste means waste containing radionuclides (1) where more than ten percent of the initial activity of a radionuclide remains after 10,000 years (e.g., long-lived parent), (2) where the peak activity from progeny occurs after 10,000 years (e.g., long-lived parent – short-lived progeny), or (3) where more than ten percent of the peak activity of a radionuclide (including progeny) within 10,000 years remains after 10,000 years (e.g., short-lived parent – long-lived progeny). The first part of the definition represents radionuclides with approximately a 3,000 year or longer half-life. Examples of isotopes that are short-lived but produce long-lived progeny are provided in Table 7-1 (e.g., Am-241, Cm-242).

Table 7-1 Long-lived Isotopes Potentially Present in LLW Performance Assessment Inventories

Isotope	Half-life (yr)	Long-lived		LLW PA Inventory[1]	Isotope	Half-life (yr)	Long-lived		LLW PA Inventory[1]
		Parent	Progeny[2]				Parent	Progeny[2]	
Al-26	7.17×10^{5}	X			U-233	1.59×10^{5}	X	Th-229	Yes
C-14	5,730	X		Yes	U-234	2.45×10^{5}	X	Th-230	Yes
Cl-36	3.01×10^{5}	X		Yes	U-235	7.038×10^{8}	X	Pa-231	Yes
K-40	1.3×10^{9}	X			U-236	2.342×10^{6}	X	Th-232	Yes
Ni-59	7.5×10^{4}	X		Yes	U-238	4.468×10^{9}		U-234	Yes
Se-79	1.1×10^{6}	X			Np-237	2.14×10^{6}	X	U-233	Yes
Zr-93	1.53×10^{6}	X			Pu-238	87.7		U-234	Yes
Nb-94	2.0×10^{4}	X			Pu-239	2.41×10^{4}	X	U-235	Yes
Tc-99	2.14×10^{5}	X		Yes	Pu-240	6.54×10^{3}	X	U-236	Yes
Pd-107	6.56×10^{6}	X			Pu-241	14.4		Np-237	Yes
Sn-126	1×10^{5}	X			Pu-242	3.76×10^{5}	X	U-238	Yes
I-129	1.6×10^{7}	X		Yes	Pu-244	8.26×10^{7}	X	Pu-240	
Cs-135	3×10^{6}	X			Am-241	432		Np-237	Yes
Sm-146	1×10^{8}	X			Am-242m	16 hr		U-234	Yes
Pm-147	2.62		Sm-147		Am-243	7.38×10^{3}	X	Pu-239	Yes
Sm-147	1.06×10^{11}	X			Cm-242	0.446		U-234	
Eu-152	13.3		Gd-152		Cm-243	28.5		Am-243	
Gd-152	1.08×10^{14}	X			Cm-244	18.1		Pu-240	
Ra-226	1,600	X		Yes	Cm-245	8.5×10^{3}	X	Np-237	
Th-229	7.3×10^{3}	X		Yes	Cm-247	1.56×10^{7}	X	Am-243	
Th-230	7.7×10^{4}	X	Ra-226	Yes	Cm-248	3.39×10^{5}	X	Pu-244	
Th-232	1.41×10^{10}	X		Yes	Cf-249	351		Cm-245	
Pa-231	3.28×10^{4}	X			Cf-251	898		Am-243	
U-233	1.59×10^{5}	X	Th-229	Yes	Cf-252	2.64		Cm-248	

[1] Any isotope that is to be disposed of in sufficient quantities should be considered as part of the LLW PA inventory. However, the isotopes with "Yes" are expected to more commonly be a significant isotope in a LLW PA inventory based on past analyses as of the date of this publication. All progeny important for the radiological dose calculations should be considered in the technical analyses. For example, Rn-222 is an important short-lived progeny of Ra-226.

[2] Only the first long-lived progeny encountered in decay chains are listed in this column.

Table 7-2 Expected Level of Review Effort Associated With Performance Period Analyses

Radiation Hazard And Duration	Level Of Review Effort	Example
Short-lived, any concentrations	NA	Long-term performance period analyses are not necessary.
Short-lived and low concentrations of long-lived or limited quantities of concentrated long-lived	Low	Using undisturbed concentrations during the performance period, provide analyses showing that the dose to inadvertent intruders meets the compliance period performance objective (e.g., assume no dilution and perform an intruder assessment).
Moderate concentrations of long-lived or moderate quantities of concentrated long-lived	Moderate	Provide analyses showing that the disposal system will limit releases from natural processes and plausible disruptive events[1]. Estimate the range of doses that may result to intruders and members of the public and demonstrate that they are minimized to the extent reasonably achievable[2]. Include uncertainty and variability. Formal peer review of the analyses and results should be considered.
High-concentrations and quantities of long-lived	High	Provide analyses showing that the disposal system will limit releases from natural processes and plausible disruptive events. Estimate the range of doses that may result to members of the public and demonstrate that they are minimized to the extent reasonably achievable. Include uncertainty and variability. Support for the range of impacts should include model support, such as that derived from natural analogs of long-term site evolution. Independent, formal peer review of the analyses, results, and model support should be performed.

[1] Discussed in Section 7.3
[2] Discussed in Section 7.4.1.1.3

Licensees should provide model support for the performance period analyses; however, that support will likely be less quantitative and involve more expert judgment than model support that would be required for the compliance period and the protective assurance period. Table 7-2 shows how the performance period analyses may be risk-informed by licensees. Review methods other than those suggested by the examples in the table may be suitable. The level of review effort should be higher when risks for the performance period are larger. If at all possible, simple, conservative analyses should be used, especially when projected risks are low. For higher hazard and longer-lived wastes, expected scenarios as well as less likely, but plausible, disruptive scenarios (discussed in Section 7.3) should be addressed in the analyses. Licensees should provide model support, as discussed in Section 2.2.3, especially for higher hazard and longer-lived wastes. In order to determine what hazard is posed, it may be useful for licensees to estimate the doses to intruders and public receptors with conservative scenarios and compare those estimates to their expected scenarios. A hazard may or may not translate into risk, but high hazard problems should have more support and independent review relative to low hazard problems.

The NRC staff developed the concentration values provided in 10 CFR 61.13(e) as a risk-informed screening device to help determine if performance period analyses are necessary for a particular disposal action. The challenge associated with developing criteria for when to perform the performance period analyses, such as these concentration values, is that there are many variables that can influence the magnitude of the impact from the disposal of a particular type of waste. Site-specific design and hydrogeology as well as potential disruptive processes and events will influence which pathways are important and the magnitude of risk associated with the different pathways. In most circumstances, the variability in the analyses results will be larger for calculations supporting demonstration of compliance with 10 CFR 61.41 than those associated with 10 CFR 61.42.

A key driver of variability in the risk associated with long-lived, mobile isotopes is variability in hydrogeology. The disposal of wastes containing long-lived isotopes near or at the Class A limits can result in drinking water doses that exceed 0.25 mSv/yr (25 mrem/yr) at certain sites. Depending on the site-specific hydrogeology, these water pathway impacts may occur during the compliance period, during the protective assurance period, or during the performance period. For example, it was previously found that the isotopes ^{129}I, ^{99}Tc, ^{36}Cl, and ^{14}C are most problematic because of their relatively high mobility in the environment (NRC, 1982b, p. 5-43). Though the drinking water pathway is discussed in the text above, the concept is not limited to the drinking water pathway. Various site-specific conditions can drive the risk from waste disposal at a site even for waste at the Class A limits (i.e., waste that is generally perceived by most licensees and stakeholders to be fairly benign). The assumption that disposal of Class A waste is inherently compliant with the performance objectives may not always be correct, particularly for waste classified using 10 CFR 61.55(a)(6).

Some sites, designs, and waste streams may require performance period analyses even though the average concentrations of long-lived radionuclides are below those provided in 10 CFR 61.13(e). The types of site-specific conditions that could trigger the need to conduct performance period analyses include, but are not limited to:

- Limited dilution or dispersion (e.g., sites with high infiltration and low groundwater velocities) at a site with a potable groundwater pathway and long travel times.

- Highly-soluble wasteforms combined with resistive engineered barriers that fail discretely.
- Ingrowth of progeny that increases the radiotoxicity of the waste significantly during the performance period compared to the radiotoxicity at the end of the compliance period.
- Erosion rates and engineered barrier performance that result in limited protective cover remaining over the waste during the performance period.
- Gaseous releases from the ingrowth of radon being a significant exposure pathway during the performance period.

The importance of the conditions described above is conditional on the timing (i.e., delay) of a potential radioactive release. However, delay by itself is generally not enough to result in a significant impact during the performance period from waste disposal at the Class A limits. One or more of the conditions listed above must also be present. Although the travel time concept presented here is focused on the time from release to exposure of the public, it is not limited to hydrologic transport through groundwater. Transport through surface water or the atmosphere could also be considered though the travel times through those pathways are generally much shorter. Performance period analyses are required when the isotopic concentrations exceed the values specified in 10 CFR 61.13(e), or if site-specific conditions warrant confirmation that the performance objectives will be met (see Example 7.1).

7.1 Estimation of Disposal Site-Averaged Isotopic Concentrations

Table 7-3 in this document is the same as Table A in 10 CFR 61.13(e). It provides the concentrations values that a licensee must use to determine if performance period analyses are necessary for their proposed disposal action. These concentration values, for radionuclides other than the long-lived alpha-emitting non-transuranic isotopes, are the Class A waste concentrations provided in Table 1 of 10 CFR 61.55. Long-lived alpha-emitting non-transuranic isotopes are included at the same concentrations as the long-lived transuranic isotopes. During the original development of the 10 CFR 61.55 waste classification tables, long-lived alpha-emitting non-transuranic isotopes were not included because it was expected that LLW would not contain those isotopes in sufficient quantities and concentrations to impact public health and safety from their disposal (NRC, 1982b). However, there is no compelling reason for the long-lived non-transuranic isotopes to be treated differently in the technical analyses if both transuranic and non-transuranic isotopes are included in the wastes proposed for disposal. The radiological risk will be determined in part by the dose conversion factors of individual isotopes and the concentration of those isotopes. There is variability in dose conversion factors from isotope to isotope (EPA, 1988). NRC decided to reduce this variability when deriving the 10 nanocuries per gram (nCi/g) concentration value for all transuranic isotopes in Class A waste (NRC, 1982b). The dose conversion factors for non-transuranic isotopes are generally comparable to the transuranic isotopes, and NRC believes it is appropriate to simplify the consideration of variability. The concentrations provided in Table A of 10 CFR 61.13(e) are only to determine if performance period analyses are necessary.

Example 7.1

A disposal site is located in a humid, oxidizing environment with a shallow water table and potable groundwater. Infiltration that will flow through the waste to the saturated zone is not expected to experience significant dilution. The groundwater flow velocity is relatively slow, such that most of the discharge from the aquifer is balanced by recharge from infiltration. In order to control infiltration, the licensee intends to use geomembranes with a design-life of approximately 1,500 years. The water table is located within a geologic unit that is mostly clay with good properties with respect to slowing radionuclide transport. The waste streams being disposed of are dominated by Tc-99 and material contaminated with soluble forms of DU.

Conclusion: The licensee develops waste acceptance criteria that specify isotopic concentrations for anticipated waste streams such that the sum of fractions on a disposal site-averaged basis is ≤ 0.5 of the Table A values in 10 CFR 61.13(e), thereby limiting the types of waste that can be received to concentrations less than the Table A values in 10 CFR 61.13(e). The licensee develops compliance period calculations that show the performance objectives are likely to be met for the next 10,000 years, primarily as a result of the long travel times from the waste to a potential receptor location. Their intruder assessment shows that potential impacts to intruders are well within the established limits. Because the site has a number of characteristics that could result in significant performance period impacts (e.g., resistive engineered barriers, soluble waste streams, limited dilution, waste with ingrowth of progeny, and long travel times), the licensee develops performance period analyses to demonstrate that 10 CFR 61.41(c) is met. The licensee chooses to extend the compliance period analyses with conservative parameters to provide a comparison of the estimated impacts during the performance period with those for the compliance period.

A licensee should estimate the disposal site-averaged isotopic concentrations of radionuclides to determine if performance period analyses are necessary. Disposal site-averaged concentrations can include the volume of the waste, uncontaminated materials used to stabilize waste or reduce void space within waste packages, the volume of uncontaminated materials placed within the disposal cells, and the volume of engineered or natural materials used to construct the disposal cells. For the purpose of determining if performance period analyses are necessary, the licensee should base the disposal site-averaged concentrations on the total amount of waste averaged over the total volume of all disposal cells. Though the disposal site definition includes a buffer zone, the buffer zone should not be included in the calculations. For radionuclides where the concentration shown in Table 7-3 is based on mass and not volume, the licensee can use the total mass of the different materials within the disposal cells.

A reviewer should consider the variability in radionuclide concentrations over the disposal site. The significance of variability will need to be interpreted in the context of the particular technical analysis. For the purposes of determining if performance period analyses should be performed by a licensee, the variability in concentrations of radionuclides over the disposal site should translate into a significant change in a performance metric (e.g., dose, environmental concentration, flux rate to the environment). Some metrics will be more sensitive to inter-site variability in radionuclide concentrations than others, as a result of different averaging volumes when calculating the metric. For instance, the concentrations in an aquifer may have more variability compared to a drinking water dose metric because the aquifer concentrations are averaged over some volume, due to extraction of the aquifer water in a well, in order to calculate the drinking water dose (i.e., wellbore dilution).

Most disposal facilities are expected to dispose of waste containing a mixture of different isotopes. In order to determine if performance period analyses are necessary, a sum of fractions approach must be used, as required by 10 CFR 61.13(e). Licensees should estimate the disposal site-averaged concentrations of each isotope. They should divide the resultant values by the concentrations found in Table 7-3 to estimate a fraction for each isotope, and then sum the fractions over all isotopes. If the total is greater than 1.0, then licensees are required to develop performance period analyses (10 CFR 61.13(e)). Examples 7.2 and 7.3 provide sum of fractions (SOF) calculations.

Table 7-3 Disposal Site-Averaged Isotopic Concentrations that Require Performance Period Analyses

Radionuclide	Concentration (Ci/m^3)
C-14	0.8
C-14 in activated metal	8
Ni-59 in activated metal	22
Nb-94 in activated metal	0.02
Tc-99	0.3
I-129	0.008
Long-lived alpha-emitting nuclides	[1] 10
Pu-241	[1] 350
Cm-242	[1] 2,000

[1] Units are nCi/g

7.2 Disposal Site Characteristics that Enhance Long-Term Isolation

The remainder of this section focuses on the long-term analyses that licensees should complete. The regulatory requirements are not prescriptive with respect to the type of analyses that must be performed. Licensees may use any analyses (e.g., screening, quantitative probabilistic) considered sufficient to demonstrate that the regulatory requirements will be met. However, there are limits to the analyses of projected performance over very long timeframes (e.g., tens of thousands of years) and how much confidence a licensee should place in the results of the analyses. Disposal sites and near-surface disposal facility designs that have more disposal site characteristics that enhance long-term isolation may be more likely to achieve long-term isolation of waste from the accessible environment if they demonstrate one or more of the characteristics cited in Table 7-4.

Example 7.2

The total volume of disposal cells for existing waste is 400,000 m^3. The inventory of waste located in the facility is comprised of: 50,000 m^3 of C-14 containing waste at 0.2 Ci/m^3, 200,000 m^3 of waste containing C-14 at 0.1 Ci/m^3 and I-129 at 0.002 Ci/m^3, and 50,000 m^3 of Tc-99 containing waste at 0.01 Ci/m^3. The uncontaminated fill and material used to construct the cells represents 100,000 m^3.

Conclusion: The licensee uses the values in Table A to calculate the volume-averaged SOF per the following equation. This equation is used to calculate the SOF for *n* waste streams containing *m* isotopes. *V* is the volume, *C* is the concentration on a volumetric basis, and *CA* is the value from Table A for the particular isotope.

$$SOF = \frac{1}{V_T}\sum_{i=1}^{n}\left(V_i \sum_{j=1}^{m}\frac{C_{i,j}}{CA_{i,j}}\right)$$

$$SOF = \frac{1}{400{,}000\ m^3} * \left(50{,}000\ m^3\left(\frac{0.2}{0.8}\right) + 200{,}000\ m^3\left(\frac{0.1}{0.8}+\frac{0.002}{0.008}\right) + 50{,}000\ m^3\left(\frac{0.01}{0.3}\right)\right) = 0.223$$

Because the SOF is less than 1, performance period analyses are not required.

Table 7-4 describes the characteristics that will enhance isolation at most, but not all, disposal sites. Individual characteristics may not apply at a specific site. For example, low porosity in a cementitious wasteform generally reduces the potential for subsidence and reduces leaching. However, use of a low porosity cementitious wasteform in a cold climate may result in freeze-thaw damage that could contribute to release over the long-term. While use of robust, low-porosity wasteforms is generally favorable, in this specific example it may not be. Some of the characteristics listed in Table 7-4 apply to the design of disposal facilities while others apply to the site characteristics.

7.3 Scope of the Performance Period Analyses

The performance period analyses should provide information about the performance of the disposal system under a range of conditions that represent expected scenarios, as well as less likely, but plausible, scenarios that may have significant consequences. Licensees should consider the range of conditions consistent with the site suitability analysis (described in Section 5.0), including the FEPs analysis (Section 2.0). Less likely but plausible scenarios include those that are unlikely to be observed (e.g., as low as a 10 percent chance of occurrence over the analyses timeframe), as well as those that are expected to be observed over the analysis timeframe. Performance period analyses for various sites may have different timeframes associated with them owing to differences in radionuclide inventories as well as differences in geologic settings. Therefore, a single event frequency (i.e., 10^{-5}/yr) cannot be defined for the purposes of this particular regulatory requirement.

Example 7.3

The licensee in Example 7.2 would like to dispose of a new waste stream but they are unsure if they would need to develop performance period analyses.

The new waste stream is a particulate waste. The raw particulate waste contains average concentrations of 0.7 Ci/m^3 Tc-99, 1.2 Ci/m^3 C-14, and 90 nCi/g of long-lived, alpha-emitting radionuclides. The total volume of raw waste is 100,000 m^3. In order to reduce the potential for dispersion, the particulate waste is solidified in grout prior to disposal. The ratio of grout to waste inside the disposal package is 3 to 1 (stabilizer ratio). Because the density of the grout and this particular waste stream are similar, the 3 to 1 ratio holds for both a mass and volume basis.

The drums of waste will be stacked within the disposal cells achieving a disposal cell packing efficiency of 67% (i.e., the ratio of cell volume occupied by waste packages to the total internal volume of the cell – *Cell Eff.*). In addition, the disposal cells are constructed of a variety of natural materials to provide structural stability, to reduce water inflow to the waste, and to provide chemical retention of the waste. The volume of material comprising the disposal cells is 30% of the total internal cell volume available for disposal (i.e., *Inert frac.*).

Conclusion: First the licensee calculates the cell volume required for the new waste, V_{Tn}:

$$V_{Tn} = Waste\ Volume * (1 + Stabilizer\ Ratio) * \frac{1}{Cell\,Eff.} * (1 + Inert\ frac.)$$

$$V_{Tn} = 100{,}000\ m^3 * (1+3) * \frac{1}{0.67} * (1+0.3) = 776{,}000\ m^3$$

Next the licensee calculates the SOF for the new waste stream (SOF_n) containing m isotopes, where C_m, V, and CA_m are the concentration, volume, and long-lived waste concentration (for isotope m from Table A of 10 CFR 61.13(e)). Only one new waste stream is considered, so the equation from Example 6.2 is simplified:

$$SOF_n = \frac{V}{V_{Tn}} \sum_{i=1}^{m} \frac{C_i}{CA_i}$$

$$SOF_n = \frac{100{,}000}{776{,}000}\left(\frac{0.7}{0.3} + \frac{1.2}{0.8} + \frac{90}{10}\right) = 1.65$$

Then the licensee calculates the average sum of fractions for both old and new waste where V_T is the combined volume of old and new waste (total disposal cell volumes) and SOF_o is the sum of fractions for the old waste:

$$SOF = \frac{1}{V_T} * (SOF_n * V_{Tn} + SOF_o * V_{TO})$$

$$SOF = \frac{1}{(776{,}000 + 400{,}000)} * (1.65 * 776{,}000 + 0.223 * 400{,}000) = 1.16$$

In this case the SOF is greater than 1 on a disposal site-averaged basis when the new waste stream is combined with the existing waste stream. Therefore, performance period analyses are required to determine if the new waste stream can be safely disposed of in the facility.

Table 7-4 Disposal Site Characteristics that Could Enhance Long-Term Isolation

Characteristic[1]	Description
Simple, passive designs	Simple designs are less likely to experience unforeseen failure mechanisms; passive designs do not rely on active monitoring and maintenance
Designs that mimic natural features	Stable natural features may provide indication of design characteristics that may help achieve long-term isolation
Low relief designs	Designs with low relief (e.g., buried) will experience lower rates of erosion
Low water contact with waste	Release and instability are generally associated with mass transfer. Limited water contact reduces rates of aqueous phase mass transfer
Robust, low-porosity wasteforms	Durable, low-porosity wasteforms enhance long-term stability by limiting consolidation and subsidence
Geochemical compatibility of the waste and disposal environment	Waste that is geochemically compatible with the disposal environment is less likely to experience significant release into the environment
Stable disposal environment conditions	Physically and chemically unstable environmental conditions contribute to long-term instability. For example, leaching from waste can be highest in zones of water table fluctuation
Accreting environments	Disposal systems that are gaining mass over time contribute to waste isolation by working with the natural processes instead of against them
Large distance to water table and homogeneous natural materials	The unsaturated zone can provide a significant barrier to releases to an aquifer, especially if the natural materials are relatively uniform which contributes to confidence in the performance of sorptive materials
Deep disposal	Many disruptive processes are more dynamic, complex, and more likely for shallow disposal compared to deeper disposal
Limited natural resources	A disposal system with limited natural resources decreases the likelihood of anthropogenic processes or events impacting the disposal facility or site
Stable climate	Disposal systems located in a more stable climate are less likely to experience impacts from climate variation
Low frequency of geologic and tectonic events	Over the long term, disposal systems that are located in areas of low geologic and tectonic activity are more likely to achieve waste isolation from the environment

[1] Highlighted characteristics are associated with 10 CFR 61.50 site suitability characteristics

FEPs defining the natural and engineered systems as well as assumptions about future human behavior will be needed for the performance period analyses. The challenge for performance period analyses is to provide credible assessments of the future evolution of the disposal system while avoiding open-ended speculation. Near-surface disposal introduces specific challenges over the long-term because environmental processes can have complex, dynamic, and nonlinear responses. The NRC staff believes that the approach recommended in the following sections is suitable for defining the scope of the performance period analyses for near-surface disposal. The goal of the long-term analyses is to understand the safety implications of the type of waste being disposed in the near surface and not to precisely estimate the future evolution of the surface of the earth. The goal is to provide a perspective on how the hazard may evolve over time (e.g., persistence of long-lived radionuclides and potential for ingrowth of risk significant daughters) and implications for near surface disposal.

Disposal of high-specific activity waste, if improperly managed by a licensee, poses the greatest radiological risk to public health and safety. It would be very difficult for a licensee to demonstrate with reasonable assurance that public health and safety is protected from the disposal of the high-specific activity waste at a site with unfavorable site characteristics because the margin for error is small. For example, accidental release of a relatively small quantity of Sr-90 into an aquifer at the West Valley Demonstration Project resulted in a significant ground water plume requiring remediation (NYSDEC, 2008). Only a small amount of high-specific activity waste released into the environment can cause significant problems. For the performance period, the margin for error is not as small because the high-specific activity fraction of the waste has decayed. The specific activity of the material remaining in the disposal site is much lower compared to the waste when first disposed. Furthermore, because of the long timeframes involved, a licensee may consider the performance objectives in Subpart C when evaluating whether their site meets the site suitability requirements in 10 CFR 61.50 for the performance period. For example, a disposal site might have some projected seismic activity (10 CFR 61.50(a)(4)(iii)) sometime after the 10,000-year protective assurance period. However, because of the uncertainty with events at long timeframes, future seismic activity would only disqualify the site if the licensee was unable to demonstrate that the performance objectives would be met assuming this seismic activity. Therefore, it is acceptable for the performance period for a licensee to evaluate the significance of the site characteristics using technical analyses.

7.3.1 Features, Events, and Processes

The objective of the performance period analyses is to provide information to decision-makers about disposal system performance under various scenarios. Licensees should assess the uncertainties, because they are likely to be large, and present the results of the assessment using a balanced approach. Reviewers should not hold the performance period analyses to a level of proof that is not attainable. In comparison with the compliance period, the performance period analyses will be more susceptible to bias because objective supporting information will be more limited.

Different near-surface LLW disposal facilities may have significantly different characteristics and may contain different wastes. The FEPs for one disposal site may be substantially different from those at a different site. Identification of the FEPs relevant to the performance period will be site-specific. Section 2.5 describes the FEP process that may be used by a licensee to develop the scope of the technical analyses (e.g., performance assessment). This section of the guidance document does not reiterate the general information relevant to FEPs analysis found in Section 2.5.

A licensee may extend compliance period or protective assurance calculations without modification provided that the calculations are complete with respect to including key FEPs relevant to the performance period. The compliance or protective assurance period calculations may not be complete with respect to the scope of the performance period analyses. It will be necessary for the licensee to communicate the additional uncertainties associated with events and processes that may occur in the long-term performance period if they are not represented in the compliance or protective assurance period analyses. The analyses that are developed for the compliance period or protective assurance period may not be sufficient for the performance period analyses if (1) disruptive processes are expected to occur during the performance period that have not been included in the compliance period or protective assurance period analyses, or (2) if the cumulative impact from repetitive events over the longer timeframes is not included and the repetition of those processes and events could lead to significant impacts. It is appropriate for a licensee to consider potentially beneficial natural processes (from a risk reduction perspective) such as dispersion and dilution in addition to detrimental processes. In general, the greater the geological and geomorphological stability a potential disposal site possesses, the greater the likelihood that FEPs that may occur in the performance period will have already been represented in the licensee's compliance period or protective assurance period analyses. However, the representation of a particular FEP in the compliance period or protective assurance period analyses may be different in the performance period analyses. Even if the same set of FEPs may be appropriate for all analyses, they may be represented differently in each analysis.

As discussed in Section 2.5.3.1, 10 CFR Part 61.50 provides the disposal site suitability requirements for the land disposal of LLW. The process to determine if some of these criteria will be met is complementary to the FEPs process (discussed in Section 7.3.2). The criteria from 10 CFR Part 61.50 that best lend themselves to FEPs analysis are 10 CFR 61.50(a)(2)(i-iv) and 10 CFR 61.50(a)(4)(ii-iv). Some of the 10 CFR 61.50 regulatory requirements list FEPs that a disposal facility must have (e.g., sufficient depth to water table), whereas other requirements list FEPs or conditions that a disposal facility must not have (e.g., exploitable natural resources). Since these are regulatory requirements, the FEPs process for the performance period should analyze the FEPs related to 10 CFR 61.50(a)(2)(i-iv) and 10 CFR 61.50(a)(4)(ii-iv).

Many potential scenarios involving certain forms of flooding, landslides, earthquakes, and volcanoes will not be evaluated in the performance period. Potential sites containing FEPs that occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of 10 CFR Part 61 Subpart C for the compliance period would not be considered for LLW disposal. These scenarios may also preclude defensible modeling and prediction of long-term impacts.

The number of possible scenarios that can be developed will be reduced after screening potential disposal systems based on the site suitability FEPs. However, FEPs that have been screened from further consideration in the compliance period or protective assurance period may not be able to be screened from further consideration for the performance period analyses. For example, the rate of erosion may be estimated to be sufficiently low over the compliance period, and as a result, the FEP of erosion is not within the scope of the compliance period analyses. However, over the analyses timeframe for the performance period the rate of erosion may be significant such that the FEP should be included within the scope of the performance period analyses. Therefore, the compliance period and protective assurance period FEP processes will reduce the FEPs applicable to the performance period but some of the FEPs eliminated in the compliance period or protective assurance period may apply for the performance period.

7.3.2 Screening of Features, Events, and Processes Based on the Requirements in 10 CFR 61.50

A licensee should complete the FEP screening and scenario development process for the performance period in a risk-informed manner. Whereas some of the site characteristics for the compliance period are either required to be present or to be absent (i.e., hydrological site characteristics for 500 years) because they are precursors of poor long-term performance, all of the site suitability characteristics for the performance period may be evaluated considering radiological risk.

Appendix B presents hazard maps that the NRC staff created related to the features and phenomena of the 10 CFR 61.50 criteria. The hazard maps provide an illustration of the FEPs associated with the site suitability requirements. The maps cannot be displayed in this document at sufficient size to be used to determine if any specific location would be impacted by one of these phenomena. The figures only provide an illustration of potentially impacted areas.

Regulators should not use the hazard maps in Appendix B to prohibit disposal because the resolution of the maps and the precision and accuracy of the techniques used to generate them may not be sufficient for site-specific evaluations. However, regulators should use the maps to determine when greater review effort and more technical basis should be expected for a licensee's site-specific evaluation. In addition, the data used to produce these maps could be used, via Geographic Information System (GIS) software, to perform screening-level FEPs analyses. However, the data used to produce these figures in Appendix A were not collected at a scale of resolution sufficient to perform detailed site-specific evaluations by either regulators or applicants.

For the performance period analyses, FEPs screening based on the requirements in 10 CFR 61.50 does not need to be resource intensive relative to the other steps in completing the technical analyses. Background information and knowledge of the geologic history of the site can be used by qualified specialist(s) to evaluate the likelihood of a FEP being present at a potential disposal site during the performance period. This evaluation is a qualitative exercise using information on the past history of a disposal system. The phenomena and features that have occurred there in the past can be used to make judgments about the future and to help make screening determinations. For example, a disposal system may be near a current floodplain but outside of the influence of its associated processes. A qualified specialist may examine the location, nearby topography, and the past history and events, and be able to provide information on the potential for future floodplain formation at the disposal site. With diverse information drawn together from various sources, a licensee may be able to create a sufficient technical basis that supports the exclusion of a floodplain or a near-surface water table forming at or near the proposed disposal site for at least 10,000 years. However, for the performance period, information from the disposal system may point to renewed flooding of the area or it may simply be insufficient to form a basis to screen the process out. In such a case, the licensee would include floodplain formation in the assessment for the performance period.

7.3.3 Future Human Behavior

FEPs that describe future human behavior in the performance period should be consistent with present knowledge of the conditions in the region surrounding the disposal system. It is not necessary for a licensee to project changes in society, changes in human biology, or increases or decreases in human knowledge or technology. The selection of receptor scenarios and exposure pathways in the performance period analyses should be limited to the consideration of the natural variability in conditions, processes, and events.

Over long timeframes, the future environmental conditions may be significantly different from the present day. If shorter term analyses limited the behavior, characteristics, and pathways of receptors based on present-day conditions, the licensee should assess the impact from *significant* changes in climatic or environmental conditions using stylized receptor scenarios (see Sections 2.2.4.1 and 2.2.4.2). As necessary, the behavior of potential receptors over the performance period should be modified using present-day climatic analog locations. For example, ground water may not be potable in the present day, but the long-term analyses could examine whether that site characteristic is robust under future climate states. If licensees were to provide a side-by-side comparison of the assumed characteristics of receptors (e.g., pathways, consumption rates, and exposure times) with those of generic “screening” receptors used in the dose analyses, the reviewer could determine the importance of the assumed receptor characteristics. This sort of comparison is strongly recommended. Generic receptor characteristics are found in a variety of documents (NRC, 1992; NRC, 1981a; NRC, 1982b). This type of comparison is also good practice for compliance period and protective assurance period assessments. Estimates of future disposal site performance that are primarily based on the engineered design, waste characteristics, and site characteristics are likely to be less speculative than estimates that rely on assumptions about future human behavior.

7.4 Analyses for Long-Lived Waste

The goal of the performance period analyses is to demonstrate how the disposal facility has been sited and designed to minimize long-term impacts and to provide an indication of the potential long-term performance. The term “analyses” is used here to describe different types of evaluations that may be performed, some of which may be quantitative and others that may be more qualitative. A description of barrier capabilities and design considerations, in addition to a conservative screening evaluation, may be sufficient for lower-risk systems (e.g., limited quantities and low concentrations of long-lived waste). Quantitative risk assessment of long-term performance may be necessary for higher-risk systems (e.g., large quantities of concentrated, long-lived waste). Figure 7-1 is a diagram of the recommended analyses approach for the performance period.

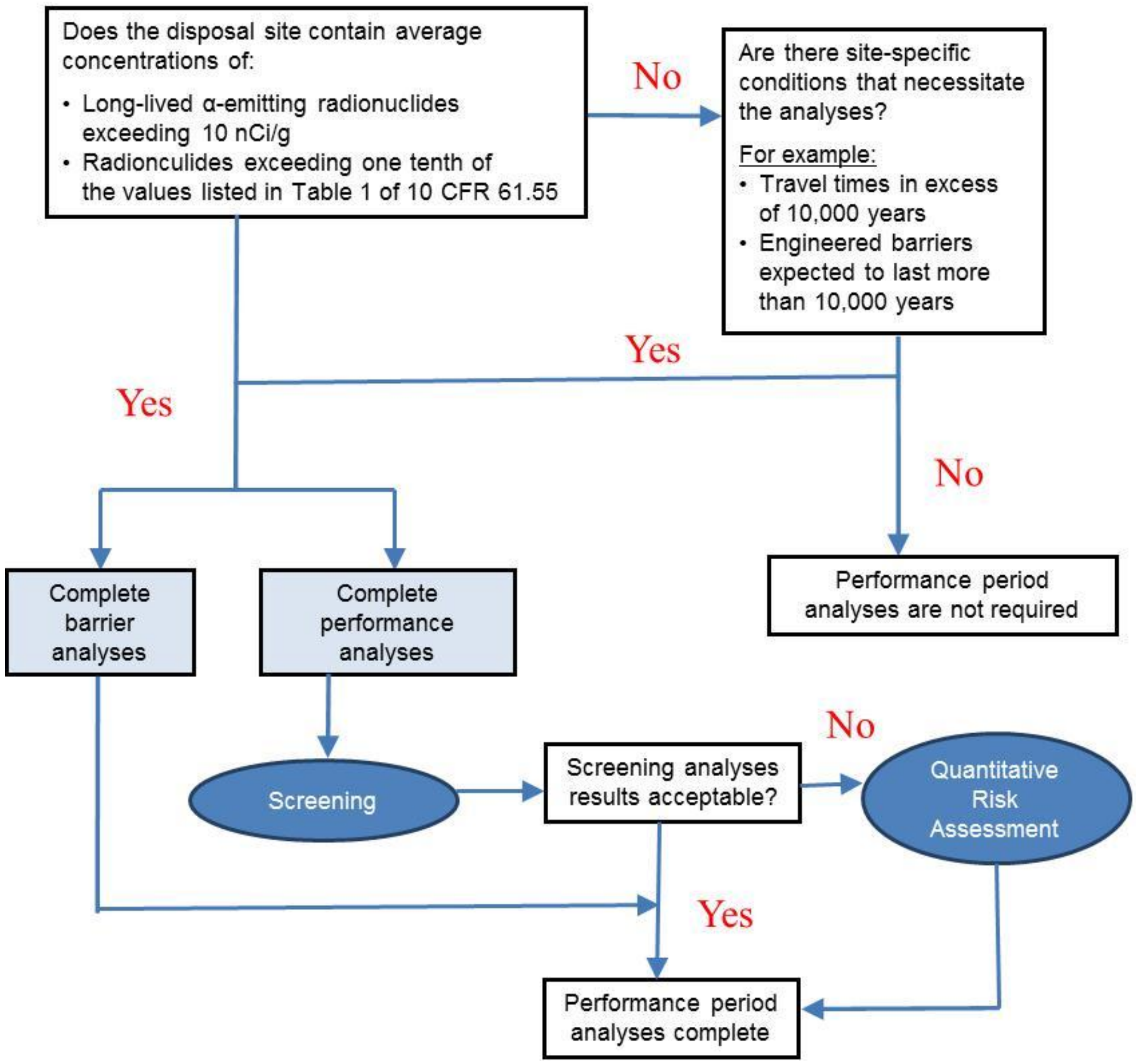

Figure 7-1 Recommended Approach to Conducting Performance Period Analysis

The analyses for the performance period are not intended to be a prediction concerning future system states of the LLW disposal system. The analyses associated with the performance period should represent a credible technical effort using available data and current scientific understanding to assess the long-term performance of the waste disposal facility, including consideration of uncertainties.

Long-term analyses may have limited data available or data that is highly variable spatially and temporally. Licensees should consider two types of data representation in their assessment of long-term impacts: expected values (e.g., central tendency) and bounding values. Use of expected values, such as the median, can convey the most likely outcome. When expected value calculations are complemented with bounding value calculations, the potential impact of uncertainty on the expected outcome can be conveyed. For the expected value calculations to be useful, the expected values must be representative of the site-specific conditions and features. Expected value calculations must have adequate supporting information to be of utility to regulators and other stakeholders. Bounding values may be necessary when data are not available or are very sparse, or formal expert judgment may be necessary.

Although the use of bounding values may be necessary, the NRC staff recommends that a licensee use caution in the use of bounding values for performance assessment or other analyses used to assess long-term performance. Many environmental systems can have complex and nonlinear responses, making selection of a bounding value for a specific parameter challenging, if not intractable. An appropriate bounding value may not be intuitive and it may only be bounding locally and not globally. In addition, the compound effect of selecting numerous bounding values in the analyses can result in non-physical results. For example, it would be unreasonable for a licensee to evaluate a high-energy disruptive process that destroys the engineered barriers of the waste disposal facility without resultant dispersion and dilution of the waste. Even in hypothetical bounding calculations, it is useful to provide some context for the reasonableness of the calculations.

7.4.1 Types of Analyses

The analyses for the performance period may be quantitative, semiquantitative or qualitative in nature, depending on the waste characteristics or other factors. As discussed previously, the performance period analyses should be risk-informed. A number of approaches are acceptable for providing information on long-term performance. The NRC staff recommends that licensees perform two sets of analyses for the performance period:

- Performance analyses to demonstrate that releases from disposal of long-lived waste will be minimized to the extent reasonably achievable for the performance period
- Barrier analyses to understand the performance of engineered and natural barriers

7.4.1.1 *Performance Analyses*

The NRC staff recommendation for conducting performance period analyses is to first employ simple, conservative screening analyses. The screening analyses may identify that the radiological risks are acceptable or that allowable limits (see Section 9.0) or other controls may be necessary. If the results of the screening analyses are not acceptable, a licensee may limit disposal of certain types of waste. In addition, quantitative performance period analyses may be performed to determine if the expected radiological risks[2] to the public from the disposal action are acceptable. The results of refined performance period analyses may demonstrate that the radiological risks are acceptable whereas the results of the conservative, screening analyses may not.

7.4.1.1.1 Screening Analyses

The recommended first step for performance period analyses is to perform simple, conservative screening analyses. The benefit of screening analyses is that they are relatively easy to perform and document, therefore, they are easier for stakeholders to review and understand, often facilitating decision-making. Screening analyses will be significantly less resource intensive for a licensee compared to full probabilistic multi-physics simulations. Screening performed with conservative parameters and calculations are not radiological risk calculations and should not be interpreted as such. They should be clearly described as hypothetical and pessimistic with the objective of identifying whether the potential for unacceptable radiological risk to a member of the public and inadvertent intruder in the performance period exists. Many beneficial features, processes, and characteristics may be purposely ignored in the calculations. If the estimated doses to the public and intruder from the screening analyses are below the limits provided in the 10 CFR 61.41(a) and 10 CFR 61.42(a) performance objectives, additional performance period analyses are not necessary.

The NRC staff cannot determine a priori the appropriate conservative screening analyses for all potential designs, waste streams, and disposal sites. Conservatism may be defined differently for different decisions. However, for all sites, licensees should provide and reviewers should evaluate:

- a list of the potential radiation exposure pathways to the public and intruder from disposed waste
- a description of the pathways expected to be most significant for releases
- the technical basis for the conservatism of the screening analyses
- a discussion of how the parameterization and representation of the screening analyses has accounted for uncertainty and variability
- a description of the barriers and processes that reduce or mitigate releases

For many disposal sites, a potable groundwater pathway will be a primary pathway for releases to the environment. A conservative screening analysis for the groundwater pathway would be one for which all waste inventory is available for release, solubility limits are not applied or are set at conservative values, and delays due to sorption during transport are eliminated by setting distribution coefficients to zero or very small values. However, the physical limitations on mass transport processes would still be included in waste release modeling. For example, if a waste container had a pore volume of X and the volumetric flow rate into the container was a small fraction of X per unit time, the exchange process should still be included in the simulation. In

[2] Other metrics such as fluxes of radionuclides in the environment or concentrations of radionuclides in the environment may also be used. However, radiological doses are used in the compliance period and provide an apples-to-apples comparison for regulatory analysis.

addition, the dilution during transport arising from the geometry of the waste, hydrogeological system, and infiltration processes should be included in the screening assessment.

7.4.1.1.2 Quantitative Analyses

If screening analyses have been performed and the projected results are not acceptable (see Section 7.4.1.1.3), then a licensee may modify their facility design, develop limitations on the types of waste that are acceptable for disposal, or perform additional analyses. A licensee may develop performance period analyses to demonstrate that the 10 CFR 61.41(c) and 10 CFR 61.42(c) requirements will be met.

In many respects, the analyses that a licensee may perform for the performance period will be similar to the performance assessment and intruder assessment completed for the compliance period and protective assurance period. The guidance provided in Sections 2.0, 3.0, and 4.0 for the compliance period and in Section 6.0 for the protective assurance period is applicable to the performance period analyses. One primary difference is that licensees will need to consider the additional uncertainties that the long timeframes associated with the performance period introduce. In addition, the metric licensees must use to determine if the 10 CFR 61.41(c) and 10 CFR 61.42(c) requirements will be met is to minimize releases to the extent reasonably achievable. Unlike the requirements presented in 10 CFR 61.41(b) and 10 CFR 61.42(b) for the protective assurance period, there is no dose goal associated with the performance period analyses.

Uncertainties associated with the performance period may be larger than those associated with the compliance or protective assurance periods. As the timeframe for the analyses is extended, temporal processes that have a rate that is insufficient to result in a significant change to performance prior to 10,000 years may be significant when evaluated for the longer performance period. For example, carbonation of a cementitious barrier may be sufficiently slow such that the passivation of rebar is not affected over the 1,000 year compliance period, and even the 10,000 year protective assurance period. However, the rate of carbonation could be sufficient enough to reduce the protective passivation of the rebar after the protective assurance period, leading to deterioration or failure of the cementitious barrier during the performance period.

Figure 7-2 is an example of the scope of the technical analyses for the compliance period, protective assurance period, and performance period for a hypothetical site. Figure 7-2 has shaded areas to show: that some processes and events will only be applicable to the compliance period or protective assurance period, that some will be only applicable to the performance period, and that others will need additional analyses to determine their applicability. The scope of the analyses for the protective assurance period may include both short- and long-term processes and events depending on the type of waste that is disposed. A licensee will assess some processes in the performance assessment for the compliance period and/or the protective assurance period, whereas others may clearly be applicable only to the performance period. In the quantitative analyses for the performance period, a licensee should assess those FEPs that were determined to be insignificant for the compliance period and/or the

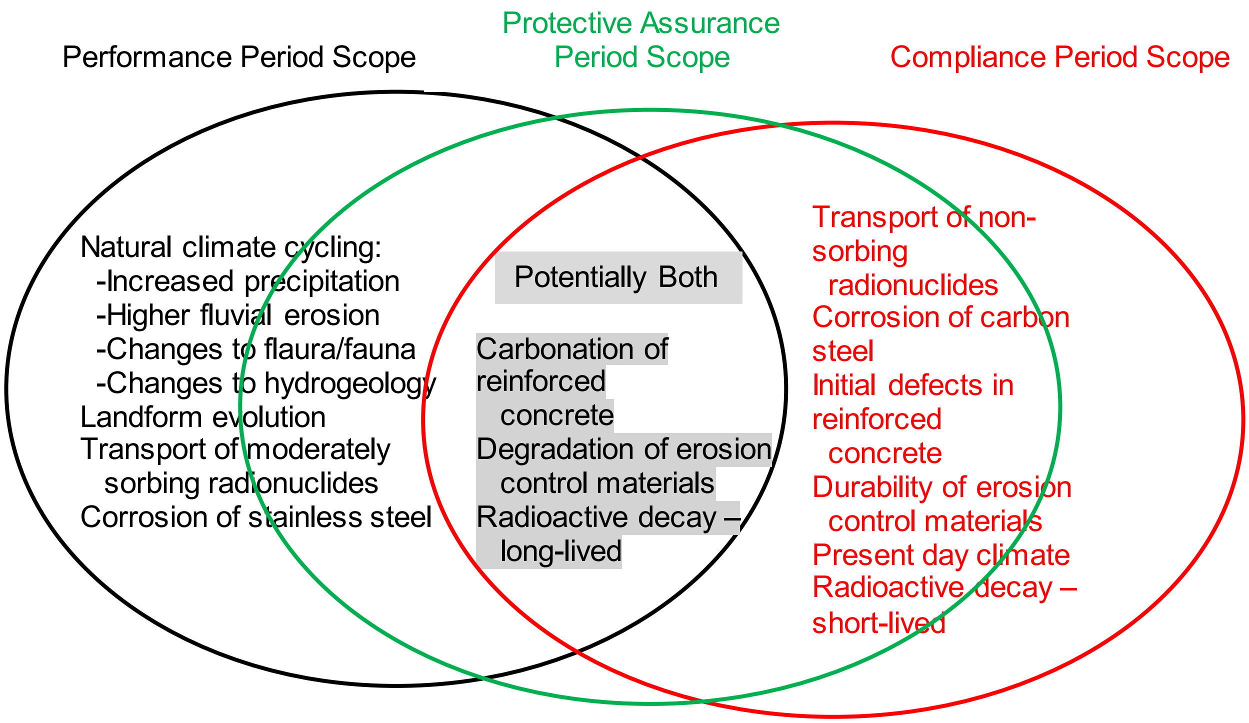

Figure 7-2 Scope of the Technical Analyses for the Compliance Period, Protective Assurance Period, and Performance Period for a Hypothetical Site

protective assurance period based on rates that were too slow or likelihoods that were too low. The licensee should determine if those FEPs are relevant to the performance period. It may be useful for a licensee to perform an iterative assessment to determine the appropriate scope of the performance period analyses.

7.4.1.1.3 Minimize Radioactive Releases to the Extent Reasonably Achievable

The performance metrics a licensee must apply to the assessment of long-term releases during the performance period is to minimize releases to the extent reasonably achievable (10 CFR 61.41(c)) and to minimize exposures to any inadvertent intruder to the extent reasonably achievable (10 CFR 61.42(c)). The metrics afford flexibility to a licensee to consider socioeconomic factors when assessing long-term protection of public health and safety. The requirements to minimize releases and exposures to the extent reasonably achievable are intended to be conceptually similar to different aspects of the ALARA requirement found in 10 CFR Part 20, optimization, and traditional cost-benefit analyses (see Section 6.0).

Dose limits are not established for the performance period in 10 CFR 61.41(c) and 10 CFR 61.42(c). A quantitative ALARA analysis cannot be completed in the traditional sense (i.e., estimate the cost for further reducing doses below a dose limit). Instead, the requirement of the performance period quantitative analyses is for a licensee to demonstrate that releases will be minimized to the extent reasonably achievable.

The NRC has developed a policy to inform regulatory decision-making (see Section 6.2.1.2).

Because of the problems associated with discounting over long timeframes, the NRC staff recommends that licensees should provide the proportion of resources that are proposed to be used to achieve protection of public health and the environment for different timeframes. These resource estimates should be provided in present day values. Timeframes to consider may include:

- the institutional control period (100 years)
- the Class C waste intruder barrier period (500 years)
- the compliance period (1,000 years)
- the protective assurance period (10,000 years)
- the performance period (site-specific values > 10,000 years)

The regulations specify individual dose limits (for the compliance period) rather than collective dose to a population. A licensee should estimate the projected individual doses for the performance period and the resources used to reduce those impacts to certain dose values or the projected cost to achieve different dose values. Dose values that a licensee may consider for comparison purposes may include the 10 CFR 61.41 public annual dose limit for the compliance period (25 mrem/yr), the 10 CFR 61.42 intruder annual dose limit for the compliance period (500 mrem/yr), the 10 CFR Part 20 public annual dose limit (100 mrem/yr), and background radiation values for the site, or other limits for which a licensee provides technical bases. Radiological doses at very long timeframes are based on many unstated assumptions. However, radiological doses provide a present day metric for stakeholders to consider. Other metrics may be appropriate for a licensee to consider, such as concentrations in the environment and flux rates. The analyses should demonstrate that a reasonable attempt has been made through site selection, facility design, and waste acceptance to minimize releases to the public to extent reasonably achievable for the performance period (see Example 7.4).

In summary, the NRC staff recommended approach to performance period analyses entails the following primary elements:

- A summary of present day resources, with no use of discounting, used to limit releases for different regulatory timeframes
- A description of the additional resources needed to achieve a greater reduction in releases during the performance period, or why further reductions are not possible
- A discussion of why additional resource usage is not warranted

Example 7.4: A disposal site is located in a semi-arid environment in an area of low-relief and long-term accretion. The waste streams proposed for disposal have a SOF of 4.3 when evaluated against the Table A concentrations in 10 CFR 61.13(e). Therefore, performance period analyses are required. Because the compliance period analyses demonstrated that the performance objectives would be met by a significant margin, the licensee elects to perform a screening analysis for the performance period by extending the compliance period calculations beyond the protective assurance period to the performance period with conservative parameters.

Conclusion: The licensee provides the regulator with a list of the potential radiation exposure pathways to the public. The dominant release pathway in the compliance period analysis was via ground water. It is anticipated that this may also be the dominant exposure pathway for the performance period analyses. The licensee performs an assessment of FEPs that were screened out of the compliance period assessment to determine if any of those phenomena are potentially significant to the performance period analyses. The only significant process identified is natural cycling of the climate. Because the site is located in the Southern US, the impact of natural cycling of climate is represented in the screening analyses by assuming a wetter and cooler climate (e.g., greater infiltration). Conservatism introduced in the screening analyses for the performance period include elimination of sorption during transport, assuming the engineered cover provides no reduction in natural recharge rates, and assuming the primarily carbon steel waste packages provide no barrier to release or transport. Because solubility limits were not applied in the compliance period analyses they are not adjusted for the performance period analyses. The receptor characteristics are adjusted to be consistent with the climate state.

The screening analyses for the performance period results in an estimated peak all pathways dose of 40 mrem/yr at 30,000 years. A sensitivity analysis on the long-term infiltration rates is included to address future climate state uncertainty. The licensee includes a comparison of the flux (g/yr) of naturally-occurring radionuclides from the disposal facility with those originating from natural sources, in a nearby river. The fluxes from the facility are less than those from natural sources.

The licensee also develops a cost comparison of some engineered alternatives to the disposal facility and how they could impact performance period doses. Only technologies that would result in a significant increase in cost or are unproven result in a significant decrease in projected impacts. Because the projected doses from the conservative screening analysis do not significantly exceed the compliance period dose limit, only a first-order assessment of technologies and their impacts is warranted.

The licensee performs barrier analyses to determine the most significant components of the system that are reducing releases. For the performance period, the licensee determines that dilution and dispersion during transport are very significant. In addition, solubility limits and sorption during transport could be very important, though they are not credited in the conservative screening analyses.

Because the compliance period scope was supplemented and conservatism was used in the analyses, the performance period analyses should be sufficient to demonstrate that releases for the performance period have been minimized to the extent practical even if the estimated doses exceed the compliance period dose limit.

7.4.1.2 *Barrier Analyses*

Licensees should use barrier analyses to identify and describe the capabilities of barriers, the challenges and stresses expected to be imposed on barriers, and the contribution of barriers to limiting or delaying releases of long-lived waste into the environment. Licensees can use different types of analyses, ranging from qualitative to quantitative, to demonstrate how the barriers of the disposal facility limit long-term impacts. Barrier and component analyses can be used to satisfy 10 CFR 61.13(e) to illustrate the long-term performance of barriers and components of an LLW disposal system. Barrier and component analyses involve decomposing the performance of the system into the performance of the components under assumed scenarios or configurations.

Licensees should provide a discussion of the capabilities of engineered and natural barriers to reduce releases or exposures. The discussion can be useful for various stakeholders to develop understanding of the disposal system performance. Events and processes that may impact those capabilities should also be discussed. A discussion of the expected persistence and durability of the barriers, and the basis for the expected durability, will be useful for many stakeholders. At long timeframes, the performance of an engineered barrier is likely to be diminished. A challenge with taking a qualitative approach to describing barrier performance is determining the actual barrier performance rather than the potential barrier performance. The potential barrier performance may not be realized because (1) the performance is deteriorated or eliminated by processes and events, or (2) because the performance is masked by the performance of other barriers, even though it is favorable to have independent, redundant barriers (see Section 8.0). In addition, as-built performance can differ from as-designed expectations. Quantification of the performance of the engineered and natural barriers is useful because the estimated performance of the barrier is represented in the calculation regardless of whether the performance is close to potential or has significantly deteriorated. Quantitative barrier analyses can reduce some of the challenges and provide estimated performance based on available information.

Semi-quantitative analyses may involve estimating the performance of individual components or materials in the disposal system and providing the basis for the performance of the component or material. For example, if a robust engineered cover using durable rock is provided for erosion protection, estimation of the durability of the rock over the long-term may provide confidence in future performance without detailed landform evolution modeling. Estimation of the ages and stability of surrounding analogous landforms may be useful in providing inferential information about the long-term stability of the waste disposal site.

Quantitative analyses, such as extension of technical analyses calculations from the compliance period and protective assurance period to the performance period, can provide estimates of the ability of the disposal system to limit long-term impacts, as long as the scope of the compliance period and protective assurance analyses is sufficient for the performance period analyses.

7.4.1.2.1 Methods

Different methods are available to perform barrier and component analyses, including, but not limited to, one-off analyses, one-on analyses, and factorial designs (Esh et al., 2001; NRC, 2004a, Eisenberg and Sagar, 2000). Typically, the term “one-off” analysis is used to refer to varying one parameter — in this case, one barrier — at a time. Barrier and component analyses are usually performed by isolating the performance of the particular barrier or component. The biggest challenge in performing these analyses is usually communicating what the results mean and how they should and should not be interpreted, because the calculations provide a hypothetical situation that may never arise (e.g., elimination of a geologic unit, or failure of all waste packages at a single instant).

Barrier and component analyses can be performed at different levels of resolution. Different levels of resolution can provide important detail to help focus the regulatory review. For example, representation of a disposal system as its components — an engineered cover, disposal vaults, wasteform, unsaturated zone, and saturated zone — can convey broadly which areas are contributing to performance in mitigating risks. Refinement of that analysis, such as looking at individual layers in a multilayer engineered cover, may identify specific areas of performance.

Barriers and components in the disposal system (e.g., engineered barriers and disposal site) may reduce the magnitude of doses or change the timing of when doses could occur. The barrier and component analyses look at changes to both the magnitude of projected doses and the timing of when those doses are projected to occur. Some barriers may impact both metrics, while others may only impact a single metric.

Environmental system models may include a range of coupling of components from weak to strong. The licensee will need to clearly identify how processes that may affect multiple components have been treated in the barrier and component analyses. In addition, disruptive processes and events may impact multiple barriers or components. Disruptive processes and events may be more important to consider during the performance period compared to the compliance period or protective assurance period because of the longer time during which they could occur. A licensee can perform barrier and component analyses after a disruptive event has been assumed to occur, in order to understand how the components of the disturbed system may be contributing to limit the impacts from the disruptive event.

One-off analyses are analyses in which the performance of a single barrier or component is neglected in order to understand the contribution of the barrier to performance when the system is operating under the anticipated range of conditions. Each barrier or component is analyzed in this manner and the relative performance, such as the change in peak dose, is compared. For example, the contribution of an engineered cover to performance could be evaluated by setting the infiltration rate into the disposal system to a value that represents a natural recharge rate in the region of the disposal facility. If the engineered cover had other contributions to performance (e.g., reducing radon fluxes) those should also be eliminated in this type of analysis. The results are best expressed on a relative basis, such as percent change, as the analyses may be unphysical. But these types of barrier analyses calculations can have value because they clearly convey which elements of the system are providing the most contribution to performance, and therefore, which elements should have the most technical basis and most rigorous review effort.

Individual components or barriers may have a redundant performance function with other components or barriers. A one-off analysis result that indicates the performance did not change when a component was “turned off” could represent that the barrier or component truly does not contribute significantly to overall performance. However, the resulting lack of estimated performance could indicate that a different barrier is providing a redundant functionality. A licensee can use different analyses, such as one-on and factorial designs, to complement the one-off type of barrier and component analyses to reveal this type of redundant functionality.

“One-on” analyses are analyses in which only a single barrier or component is represented in order to determine the potential performance of the barrier. A benefit of the one-on analysis is that it identifies the hypothetical maximum <u>consequence</u> that the waste could produce. However, the usefulness of this type of analysis is reduced when the likelihood for the hypothetical consequences becomes overly remote. One-on analyses can be useful in identifying when different barriers may be providing redundant performance functions. A disadvantage of one-on analyses is that they do not address the likelihood of the hypothetical result ever being achieved. As long as it is understood that the purpose of the analyses is to understand how barriers could contribute, misinterpretation of the results can be avoided. The base case analysis, with all barriers and components present, represents the best estimate of disposal system performance, assuming that the level of performance assigned has an adequate technical basis.

A licensee can use factorial designs to provide a more complete picture of the contribution of various barriers and components to the overall system performance. The factorial design is one in which all combinations of barriers being “on” or “off” are generated. This type of analysis can require significant resources, depending on the number of barriers and components in the system being evaluated and the computational expense of the models being evaluated. When a full factorial assessment is not practical, a licensee can consider a partial factorial assessment. The compilation and interpretation of results from a factorial barrier assessment is not straightforward. The relative change in performance will be much different depending on the number of barriers or components that may be active in the calculation. One way to overcome this problem is simply to rank the barrier contributions for each similar calculation. Example 7.5 provides additional detail on how this may be accomplished.

Barrier addition analysis is a process in which the hypothetical maximum consequence of the waste is generated. After the licensee estimates the maximum consequence, barriers or components can be added one by one until the full system is represented. A challenge with barrier addition analyses is that the sequence in which the barriers are added may influence the results prescribed to any one particular barrier. Barriers added early in the sequence are more likely to show large performance benefits than barriers added later in the sequence.

In order for barrier and component analyses to be most useful, they should be carefully performed by analysts that understand all of the components and barriers of the overall system performance. The level of underperformance assigned to a barrier or component, which is subjective, can influence the results and interpretation of the importance of that barrier or component. The level of underperformance ascribed may represent both the amount of degradation expected as well as pessimism in the estimate of performance. Licensees should clearly explain the level of underperformance and, if possible, should assign this level of underperformance based on the amount of confidence in the understanding of the performance of the barrier or component. A barrier with a strong technical basis for its performance should be much less likely to not perform than one for which the technical basis is weak or limited. Although barrier and component analyses can provide useful information to understand how a system <u>may</u> perform, the analyses may not provide a correct representation of how the system is <u>expected</u> to perform.

7.4.1.2.2 Design, Site, and Overall Performance

Differentiation between barriers that are engineered (i.e., design) and those that are natural (i.e., site) classes or types can be useful in understanding overall performance and explaining to stakeholders why the system is expected to protect public health and safety. Generally, engineered components provide greater benefit at earlier times and natural system components provide greater benefit at later times. The engineered design should be integrated into the natural site, which can make a clear separation less obvious. In addition, the NRC staff expects that natural system conditions will have a strong influence on the performance of the engineered design. In some cases, the engineered design could influence the performance of the natural system (e.g., leaching of cement that impacts sorption in the unsaturated zone or erosion of surface soils at the toe of a slope). Engineering judgment can be used to classify barrier and component types as long as the analysis is transparent and traceable. Classification is the separation of the different barriers into classes based on the type of barrier (i.e., engineered or natural). Some phenomena may be difficult to classify, for example the chemical environment inside a waste container. The goal is to provide the classification that provides the clearest understanding of overall system performance.

Example 7.5 – A disposal system has five primary barriers, #1 through #5. A factorial barrier assessment is completed. The simulations are as follows:

#1	#2	#3	#4	#5
off	on	on	on	on
on	off	on	on	on
on	on	off	on	on
on	on	on	off	on
on	on	on	on	off
off	off	on	on	on
off	on	off	on	on

[full matrix not shown]

off	off	off	on	off
off	off	off	off	on

An overall performance measure is generated by calculating the rank of the analysis result relative to the rest of the results of that class (i.e., analyses with the same number of components turned "on" or "off"), then generating the average rank over all classes.

For example the results for the one-off class are as follows:

#1	#2	#3	#4	#5
+5%	+30%	+1%	+200%	+17%

This results in the following ranks for the one-off class:

#1	#2	#3	#4	#5
4	2	5	1	3

The average change for each two-off combination is the following (any two-off that includes a #1 in the combination goes into the average change for #1):

#1	#2	#3	#4	#5
+57%	+89%	+132%	+310%	+37%

This results in the following ranks for the two-off classes:

#1	#2	#3	#4	#5
4	3	2	1	5

The average rank of each barrier averaged over each class provides a barrier importance measure:

#1	#2	#3	#4	#5	
4	2.5	3.5	1	4	(average rank for each barrier)

8.0 DEFENSE-IN-DEPTH ANALYSES

Defense-in-Depth:
The use of multiple, independent, and redundant layers of defense so that no single layer, no matter how robust, is exclusively relied upon for safety.

The core of the NRC's safety philosophy has long included the concept of defense-in-depth. The regulations at 10 CFR 61.2 define defense-in-depth as "the use of multiple, independent, and redundant layers of defense so that no single layer, no matter how robust, is exclusively relied upon". The ultimate purpose of defense-in-depth is (1) to compensate for uncertainty in the type and magnitude of safety challenges, and (2) to compensate for uncertainty in the performance of the measures that are taken to ensure safety. Consistent with the NRC's regulatory philosophy, the regulations at 10 CFR 61.13(f) require that land disposal LLW facilities demonstrate that defense-in-depth protections are included to provide reasonable assurance that the 10 CFR Part 61 performance objectives can be met.

Defense-in-depth protections are required by 10 CFR Part 61 to prevent, contain, or mitigate exposure to radioactive material according to the hazard present, the relevant scenarios, and the associated uncertainties. Defense-in-depth protections also ensure that the risks resulting from the failure of some or all of the established barriers and controls, including human errors, are maintained at an acceptably low level. These two aims help to provide reasonable assurance that the 10 CFR Part 61 performance objectives can be met, in light of the uncertainties in projecting the behavior of the land disposal facility over both the operational and post-closure periods.

To demonstrate that 10 CFR 61.13(f) is met, licensees should describe the layers of protection that ensure that the risks are properly managed. The description should identify the use of multiple layers of protection and describe how the various layers maintain independence and provide redundancy. The description of the layers of protection can be principally drawn from risk insights derived from the results of other 10 CFR Part 61.13 technical analyses (e.g., performance assessment, intruder assessment, stability analyses, and performance period analyses), although licensees may develop separate analyses for demonstrating defense-in-depth.

This chapter describes the information that a licensee should provide and a reviewer should evaluate with respect to demonstrating that a land disposal facility includes defense-in-depth protections. Sections 8.1 and 8.2 discuss NRC's defense-in-depth philosophy and elaborate on key concepts of the defense-in-depth regulatory philosophy as they apply to LLW disposal facilities, respectively. Section 8.3 provides guidance on demonstrating defense-in-depth protections during the operational and post-closure phases of the land disposal facility lifecycle.

8.1 Background on Defense-in-Depth

Defense-in-depth is a regulatory philosophy or concept that has been used since at least the 1960s in the context of ensuring nuclear reactor safety. The philosophy is intended to deliver a design that compensates for uncertainties in knowledge of facility behavior, component reliability, or operator performance that might compromise safety.

> The **Defense-in-Depth philosophy** is intended to deliver a design that compensates for uncertainties in knowledge of facility behavior, component reliability, or operator performance that might compromise safety.

In the context of nuclear reactor safety, defense-in-depth has traditionally focused on layers of protection to prevent accident initiators, contain radioactivity, and mitigate exposures through safety systems. The defense-in-depth concept has evolved from its early narrow application in the context of nuclear reactor safety to a more expansive application as an overall safety strategy for radioactive materials that includes the multiple barrier approach.

In the 1995 Policy Statement on the Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities (NRC, 1995a), the NRC recognized that complete reliance for safety cannot be placed on any *single* element of the design, maintenance, or operation of a facility. The policy statement highlighted the need for redundancy in active safety systemsand a multiple barrier approach to protect against releases. An essential property of defense-in-depth is the concept of successive barriers or layers. These barriers or layers are commonly represented within the NRC's regulatory framework in two different ways (Sorensen, et al., 1999). First, the NRC's framework requires the use of high-level layers of protection, such as the prevention of accident initiators, the quick termination of accident sequences, and the mitigation of accidents that are not successfully terminated. Second, the NRC's framework requires the use of multiple physical barriers, which are specified for particular facilities or material uses.

In 1999, the NRC's Staff Requirements Memorandum for SECY-98-144, "White Paper on Risk-Informed and Performance-Based Regulation," approved descriptions of many terms including defense-in-depth (NRC, 1999d). The SRM describes defense-in-depth as an element of the NRC's safety philosophy that employs successive compensatory measures to prevent accidents or mitigate damage if a malfunction, accident, or naturally caused event occurs at a nuclear facility. The philosophy ensures that safety will not be wholly dependent on any single element of the design, construction, maintenance, and operation of a nuclear facility. The net effect of incorporating defense-in-depth into design, construction, maintenance, and operation is that the facility or system in question tends to be more tolerant of failures, external challenges, and uncertainty in the behavior of the facility.

More recently, in NUREG-2150, the NRC has characterized defense-in-depth protections as part of the development of a holistic vision for all facilities regulated by the NRC, including land disposal facilities (NRC, 2012c). The NRC's risk-informed, performance-based characterization indicates that defense-in-depth protections (1) ensure appropriate barriers, controls, and personnel prevent, contain, and mitigate exposure to radioactive material according to the hazard present, the relevant receptor scenarios, and the associated uncertainties; and (2) ensure that the risks resulting from the failure of some or all of the established barriers and controls, including human errors, are maintained acceptably low.

As stated above, the regulations in 10 CFR Part 61.13 (f) require licensees to <u>explicitly</u> describe how the proposed disposal facility includes defense-in-depth protections. The regulations in

10 CFR Part 61 also implicitly incorporate the concept of defense-in-depth into the regulatory framework. Implicit defense-in-depth provisions of the regulations include multiple performance objectives, as well as requirements for site suitability, site design, facility operation, site closure, environmental monitoring, waste acceptance, land ownership and institutional control, and financial assurance.

8.2 Defense-in-Depth Concepts for a Land Disposal Facility

The NRC's use of the defense-in-depth philosophy is intended to deliver a design that is can handle uncertainties in knowledge of facility behavior, component reliability, or operator performance that might compromise safety. While justifiably important for nuclear facilities with large potential risks, it is similarly important for land disposal facilities for radioactive wastes, which can contain relatively large radiological hazards. Disposal facilities, being the endpoint of the nuclear fuel cycle, are responsible for containing and isolating the radioactivity for time periods far into the future. As with any estimation far into the future, uncertainty grows the farther out in time one attempts to estimate future performance as the system moves away from what is known today. The use of defense-in-depth protections is, therefore, a prudent approach to managing the uncertainty associated with estimating performance far into the future to ensure the safe disposal of radioactive wastes.

As identified in the definition of defense-in-depth at 10 CFR Part 61.2, the philosophy relies upon multiple, independent, and redundant layers of defense so that no single layer, no matter how robust, is exclusively relied upon. Multiple layers provide confidence that if an individual layer fails or underperforms, other layers of defense would be available to protect health and safety and the environment. Redundant layers provide confidence that should an individual layer fail or underperform, another layer will be available to provide similar capabilities as the individual layer to protect health and safety and the environment. Independent layers enhance confidence that the layers of defense are less likely to fail or underperform by common-cause modes in which a single event or process is able to defeat or diminish the capabilities of each layer simultaneously. In the end, multiple, independent, and redundant layers are intended to provide a margin of safety to account for uncertainty in the evolution of the land disposal facility over time. The margin of safety needed is dependent upon the hazard presented by the waste emplaced in the land disposal facility and ultimately by the potential risk of harm to health and safety and the environment. The different types of layers complement each other and when used together develop a more comprehensive approach to defense-in depth protections.

8.2.1 Multiple Layers

Multiple layers of defense provide confidence (1) that accidents can be prevented, (2) that the effects of an accident can be lessened should a malfunction or accident occur, and (3) that there is adequate protection should a layer of defense underperform due to uncertainty in its expected behavior. Reliance on multiple layers of defense ensures safety will not be wholly dependent upon any single element of the design, construction, maintenance, or operation of the land disposal facility. Multiple layers of protection use numerous, diverse protection mechanisms or actions to ensure safety. Layers of defense can consist of a number of attributes including physical or chemical barriers to radionuclide release, appropriate controls that help ensure the physical barriers perform as intended, and trained and qualified personnel who are focused on safety (see Figure 8-1).

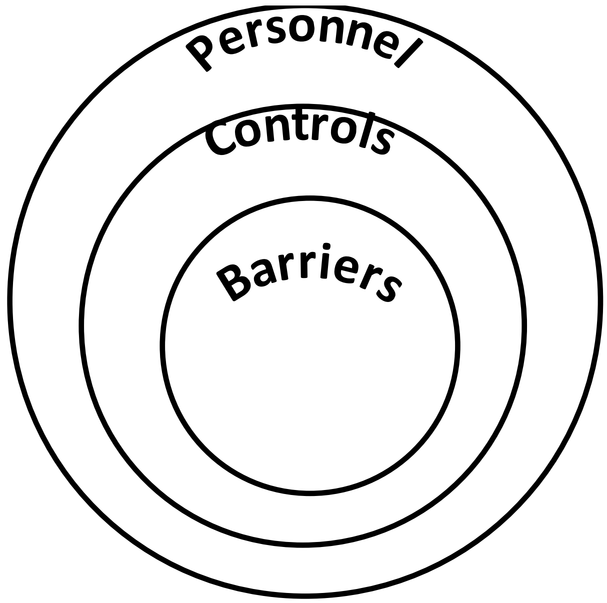

Figure 8-1 Multiple Layers of Defense

Each of the layers has an associated capability or safety function that is intended to mitigate releases and exposures to workers and the public during both normal operations and accidents. The function performed by an individual layer may be active, passive, or in some cases, a layer may provide both active and passive safety functions. Active safety functions are those that require activity or energy by the licensee to monitor and maintain protection. For example, an air filtration system requires continual maintenance, as well as an available energy source to ensure that its functionality to remove radioactive particulates is available when needed. Passive safety functions do not require ongoing activity or external energy inputs from the licensee to provide protection. For instance, a wasteform, once created, typically would not require ongoing maintenance to perform its safety function (i.e., limit the release of radionuclides), though its safety function would likely degrade over time. The role of barriers, controls, personnel, and their associated safety functions in demonstrating defense-in-depth for a land disposal facility are discussed in more detail below. For land disposal of LLW, passive layers of defense are more appropriate for the post-closure period because they do not require ongoing maintenance and monitoring. Active layers of protection are more appropriate during the operational period.

When identifying barriers, controls, or personnel relied upon for safety, licensees should clearly describe the functionality or capability provided by the barrier, control, or personnel to achieve the performance objectives and provide defense-in-depth protections. The description of the safety function should include a technical basis for the function and associated uncertainty in the function of the barrier, control, or personnel. In some cases, the safety function may only be necessary for a specific timeframe. For example, a licensee identifies a waste container as a barrier to waste release for short-lived radionuclides. The licensee should specify the time period over which the safety function provided by the waste container is necessary to demonstrate that the performance objectives are met and defense-in-depth protections are provided. Figure 8-2 depicts approximate time periods over which safety functions for barriers, controls, and personnel may be appropriate.

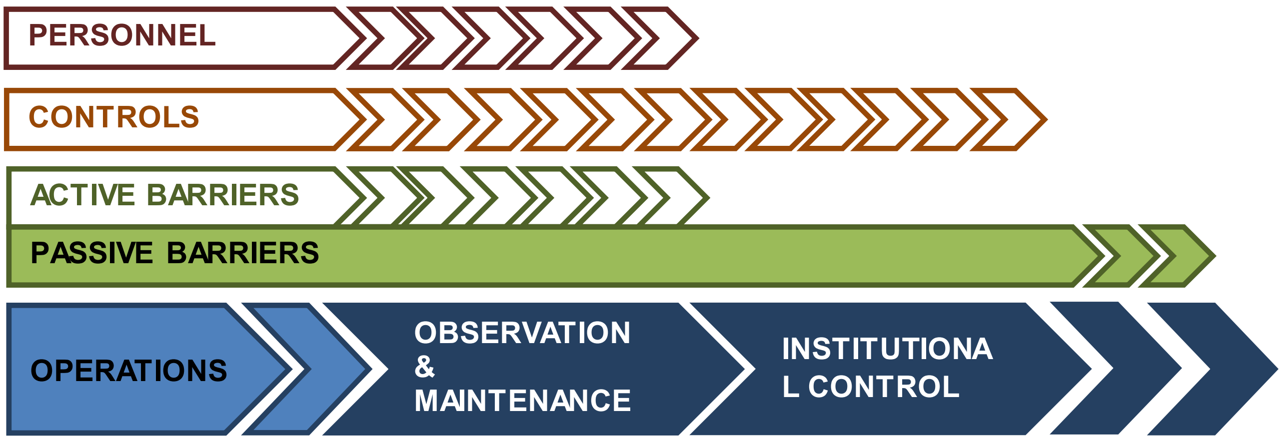

Figure 8-2 Land Disposal Facility Lifecycle and Timeframes for Defense-in-Depth Layers (Duration of lifecycle timeframes are not to scale. Dark blue timeframes are considered the post-closure period.)

8.2.1.1 *Barriers*

For the land disposal of LLW, barriers can take a number of forms, such as a container, a wasteform, a wall, or a restricted area of land. Barriers can be either engineered or natural. Barriers are intended to improve the land disposal facility’s ability to meet the 10 CFR Part 61 performance objectives and add to defense-in-depth. In the context of disposal, barrier safety functions, which are also described as barrier capabilities, are typically intended (1) to prevent or limit the contact of water with the waste, (2) to limit the release or rate of release of radioactivity from the waste, or (3) to prevent or limit biotic contact with the waste (for inadvertent intrusion). For normal operations and abnormal events (e.g., accidents), barrier safety functions are typically designed to prevent, contain, and mitigate exposure to radioactive material.

Engineered barriers at LLW disposal facilities are generally man-made features that are designed to mitigate the effect natural processes could have on the performance of the disposal facility and also limit human activities that may expose individuals to radiation or initiate or accelerate release of radioactivity from the waste through environmental pathways. The intent of engineered barriers is to improve the land disposal facility’s ability to meet the performance objectives in 10 CFR Part 61 and add to the defense-in-depth provided by the facility design and construction. Examples of engineered barriers include (1) closure caps, which are designed to limit infiltration into disposal units, and (2) waste containers and wasteforms, which may provide shielding to site workers during emplacement and preclude or limit the release of radionuclides from the disposal units once emplaced.

Natural barriers are generally barriers inherent to the disposal site that limit exposures to the waste. Examples of natural barriers include the climatic or the hydrogeologic layers of the disposal site. Limited infiltration associated with an arid climate may result in long travel times of radionuclides from the waste to underlying groundwater. Likewise, hydrogeological layers may retard the movement of radionuclides from the disposal site as a result of sorption processes.

8.2.1.2 *Controls*

A control can be an apparatus or mechanism that, through its manipulation or administration, serves to protect public health and safety and the environment around the land disposal facility. During operations, controls are intended to prevent, contain, and mitigate exposure to radioactive material at or in the vicinity of the land disposal facility. Operators also employ controls to ensure the performance of barriers during either the operational period or after closure of the land disposal facility.

Controls can largely be classified as either engineering or administrative controls. Engineering controls include any man-made apparatus that is designed to ensure the performance of a barrier or provide a level of protection independent of a barrier. For example, an engineering control may include something as simple as a visible or audible alarm as part of access control to restricted areas or more complex systems such as a fire alarm and suppression system to limit the damage from a potential fire. Administrative controls encompass a wide array of managerial mechanisms. Administrative controls include provisions related to organization and management, procedures, record keeping, material control and accounting, waste acceptance, and management review. Administrative controls can also include legal mechanisms such as land ownership, as required by 10 CFR 61.59(a).

8.2.1.3 *Personnel*

Properly trained and qualified personnel are necessary to ensure proper design, installation, operation, or administration of barriers and controls that prevent, contain, or mitigate exposure to radioactive materials. Properly trained and qualified personnel also ensure that human errors that can lead to failure of some or all of the established barriers and controls are maintained acceptably low and safety is maintained. Personnel may also be able to mitigate exposures in an accident. For example, properly trained emergency responders can mitigate potential releases of radioactivity from the land disposal facility in the case of an accident or an emergency. Because reliance on personnel inherently relies upon activity, personnel always provide active safety functions. Designated personnel may be an appropriate layer of protection during operations; however, the regulations at 10 CFR Part 61 intend that active maintenance and monitoring of the site after closure is not relied upon for safety. Therefore, the reliance on personnel for defense-in-depth protections after closure is not appropriate.

8.2.2 Independent Layers

In addition to <u>multiple</u> layers of protection, which are discussed in Section 8.2.1, the definition of defense-in-depth specified in 10 CFR Part 61 requires that the land disposal facility incorporate <u>independent</u> layers of protection. Independence applies to the safety function in that a given layer should provide a safety function that is not dependent upon other layers of defense to perform their respective safety function. For instance, a licensee may use an engineered closure cap as one barrier to limit the flow rate of water contacting the waste and an engineered wasteform as another barrier to limit the solubility of certain radionuclides in water contacting the waste. If the closure cap were to fail, resulting in a higher flow rate of water into the disposal unit, the wasteform would still be expected to maintain low concentrations of solubility-limited radionuclides in the water leaving the disposal units. In some cases, multiple layers of defense may appear to be independent, but the safety functions performed by each layer may actually be dependent. For example, a land disposal facility may dispose of waste in a metallic waste container whose safety functions are to limit the contact of water with the wasteform and release of radionuclides. In addition, the facility disposes of the waste in a metallic wasteform that is also relied upon to limit the release of radionuclides. The waste container and wasteform may appear to provide independent functionality; however, certain chemical environments could cause degradation to both the waste container and waste form simultaneously. Further, the degradation of the waste container may directly result in more rapid degradation of the wasteform, resulting in a dependency between the waste container and wasteform to limit releases of radionuclides from a disposal unit.

8.2.3 Redundant Layers

In addition to the multiple and independent layers of protection discussed above, the definition of defense-in-depth specified in 10 CFR Part 61 requires that the land disposal facility incorporate <u>redundant</u> layers of protection. The use of redundant layers increases confidence that safety is not reliant upon any single layer. Redundancy is the <u>duplication</u> of layers of defense, in order to prevent the failure of the entire disposal system if a single item or component relied upon for safety fails or provides a safety function that is less than expected. Licensees should demonstrate that the land disposal facility has redundancy for key functions relied upon for safety.

Redundancy goes beyond implementing multiple layers. Redundancy requires that the safety function performed by a layer be duplicated or even triplicated or more for safety-critical components in high-risk scenarios. The duplication of a safety function may occur within the same layer (e.g., as a redundant component) or in other layers incorporated into the siting, design, construction, maintenance, or operation of the disposal facility. For instance, different stratigraphic units beneath a disposal facility may each sufficiently retard the migration of key radionuclides, thereby, providing redundancy should the licensee’s understanding of the primary unit’s sorptive capabilities prove incorrect. In this example, licensees would also need to provide reasonable assurance that groundwater flow occurs through the stratigraphic units and that preferential flow pathways that could minimize the water contact with the stratigraphic units would not be limited.

8.2.4 Safety Margin

Safety margin is the excess functionality remaining to provide safety after the demands of a particular scenario are placed on the functionality of the layer or system. In some high-risk scenarios, additional controls on the safety functions of a layer may be necessary in order to ensure an adequate safety margin. For instance, licensees may impose a design requirement on an engineered barrier that provides confidence that the barrier’s capability exceeds the demand imposed by the scenario (e.g., by using a pre-determined safety factor). This excess capability would provide greater confidence that safe conditions are maintained during normal operations in light of uncertainties or in the event of abnormal occurrences, accidents, or disruptive events. Conversely, licensees may overestimate the demands imposed by a scenario when determining the required safety function needed from the layer of defense. The concept of the safety margin is to ensure that safety functions are sufficient to account for uncertainty in the characterization of the demands, as well as the robustness of the functionality. Safety margins can be determined for an individual layer or the entire disposal facility, but the margin for the disposal facility should be the primary interest for licensees and regulators.

Meeting the performance objectives, as demonstrated by the other 10 CFR 61.13 technical analyses, demonstrates a level of safety margin for a LLW disposal facility because the dose limits established in the performance objectives are purposefully established below the public dose limit specified in 10 CFR Part 20 (to account for the possibility of exposure from multiple facilities). Understanding the safety margin for abnormal occurrences, accidents, or disruptive events is important to provide confidence that the performance objectives can be met, even if less likely, but plausible, scenarios occur. Because abnormal occurrences, accidents, and disruptive events are plausible, but generally less likely, licensees may account for the likelihood of these events or processes occurring to determine the expected safety margin. For the post-closure periods that are concerned with projected consequences, the licensee should demonstrate that for plausible abnormal occurrences, accidents, or disruptive events the potential doses would remain below those for which intervention would be necessary if they were to occur today. Guidance on these levels is discussed in more detail in Section 8.3.3.2 for each post-closure period. Section 2.5.4 discusses the terms used to describe scenarios to be included in technical analyses (i.e., reasonably foreseeable, less likely, but plausible, and implausible). These terms and types of scenarios can also be used to demonstrate defense-in-depth protections.

8.2.5 Risk-Informed Approach

Defense-in-depth should be applied in a risk-informed manner. As the hazard from the waste increases, more robust layers of protection may be needed to account for uncertainty in the performance of the barriers, controls, and personnel used to maintain safety. Alternatively, less robust layers of defense may make additional redundancy necessary, depending upon the uncertainty in the safety functions provided by the layer(s) and the risk posed by the waste. The timeframe that the safety functions are provided by the layers of protection should be appropriate for the time period over which significant risks are presented by the waste. Also, as uncertainty in the functionality and reliability of barriers, controls, or personnel grows, additional layers of protection may be needed to provide confidence that safety can be maintained. For instance, for significant concentrations of long-lived waste, additional layers of protection may be needed to account for the uncertainty associated with projecting performance over very long time periods. Whereas, for shorter-lived hazards, fewer layers of protection or layers that provide safety functions confidently over an appropriate time period may be sufficient.

8.3 Defense-in-Depth Analyses

The regulations at 10 CFR 61.13(f) require licensees to demonstrate that defense-in-depth protections are provided for the land disposal facility. The licensee must demonstrate that defense-in-depth protections are provided and should be performed in the context of the Subpart C performance objectives, namely protection of the general population, protection of inadvertent intruders, protection of individuals during operations, and stability of the disposal site after closure. Therefore, licensees should demonstrate in a risk-informed manner that multiple, independent, and redundant layers of defense are included in the disposal system to provide confidence that no single layer will be exclusively relied upon. Demonstrating defense-in-depth also provides greater confidence that each of the performance objectives can be met. In providing layers of defense, licensees should consider the risks posed by the waste. Therefore, more layers or more robust layers may be needed for demonstrating safety will be maintained for higher risk scenarios. This section describes the role of defense-in-depth analysis required by 10 CFR Part 61 and acceptable approaches licensees may take to demonstrate that defense-in-depth protections are provided.

At a minimum, licensees should identify the defense-in-depth protections, describe the safety functions the protections perform, provide a technical basis for the safety function provided by each protection, and estimate the margin available to maintain safety. As described in Section 2.3 of this guidance, licensees should identify the regulatory requirement to demonstrate that defense-in-depth protections are included at the land disposal facility as part of the assessment context process. Thus, the defense-in-depth protections will typically be represented in the system description (see Section 2.4) and modeled in one or more of the 10 CFR 61.13(a) through (e) technical analyses, such as the performance assessment or intruder assessment, in order to demonstrate that the performance objectives will be met. Therefore, licensees should be able to draw, principally, upon the results and risk insights gained from those other analyses to identify and describe defense-in-depth protections at the land disposal facility rather than developing separate analyses for demonstrating defense-in-depth.

In some cases, licensees may need to consider whether additional features, events, and processes or alternative scenarios might be appropriate to consider solely for demonstrating that defense-in-depth protections are included (see Section 2.5). For example, a licensee may not expect a certain scenario to be reasonably foreseeable for the purposes of demonstrating that the performance objectives are met and would therefore not include such a scenario in the demonstration. However, for the purpose of demonstrating that adequate defense-in-depth protections are provided, the licensee should consider the less likely, but plausible scenario. Licensees would not need to consider scenarios that are sufficiently unlikely and can be considered implausible.

8.3.1 Identification of Defense-in-Depth Protections

Licensees should identify the defense-in-depth protections that are included at the land disposal facility. The identification of these protections, or layers of defense, should demonstrate that multiple barriers, controls or personnel are used at the land disposal facility. Section 8.2.1 provides descriptions of barriers, controls, and personnel in the context of defense-in-depth protections for a land disposal facility. Licensees should also clearly indicate when layers are included for redundancy.

The specific defense-in-depth protections for the operational versus the post-closure time periods are likely to be different because active maintenance of the site after closure is not anticipated. Following closure of the land disposal facility, defense-in-depth protections shift from a collection of active and passive barriers and controls that are used during operations to reliance on more passive barriers and controls to provide reasonable assurance that the performance objectives will be met for timeframes far into the future. This shift is necessary because the regulations at 10 CFR Part 61 specify that active maintenance of the disposal site beyond monitoring, surveillance, and minor custodial activities cannot be relied upon after the period of post-closure observation and maintenance, and without ongoing maintenance, active barriers and controls cannot be relied upon indefinitely. Defense-in-depth protections for the post-closure period may include, but are not limited to, engineered features (e.g., closure caps, wasteforms, and containers) and natural characteristics (e.g., hydrogeology) of the disposal site that are intended to contain and isolate the waste, as well as controls such as institutional controls, which are designed to limit access to the disposal site for a limited period of time, and waste acceptance requirements, which are designed to limit the radionuclide inventory in the disposal site.

The identification should be generally consistent with the key barriers, controls, or personnel relied upon in the other 10 CFR 61.13 technical analyses. In some cases, the layers identified to describe defense-in-depth may not be represented in the other 10 CFR 61.13 analyses. This may often be the case for personnel identified as a defense-in-depth protection. In these cases, licensees should provide a basis for identifying the layer as a defense-in-depth protection. In other cases, there may be less significant barriers, controls, or personnel that provide demonstrable safety functions in the other 10 CFR 61.13 technical analyses. If more significant layers of defense provide multiple layers that can be shown to be sufficiently independent and redundant, licensees would not need to identify the less significant layers as demonstrated by the other 10 CFR 61.13 analyses. In other words, a licensee does not need to identify a comprehensive list of layers of defense. Rather, a licensee only needs to identify that there are multiple, independent, and redundant layers of defense, so that no single layer is exclusively relied upon for safety.

As part of the identification, licensees should also identify which layers of defense are included for redundancy. Licensees should identify the primary layer and any associated redundant layers that are expected to be relied upon in the event the primary layer degrades or fails early. Licensees may associate a secondary layer as a redundancy for multiple primary layers and do not need to limit the association of a redundant layer with a single primary layer. In some cases, multiple layers can provide redundancy without subordinating one of the layers in the identification. The classification of primary versus secondary in this case may be in name only.

Reviewers should confirm that the licensee has identified multiple layers of defense. While licensees do not need to identify a comprehensive list, reviewers should confirm that the layers of defense identified by the licensee are generally consistent with the layers represented in the other 10 CFR 61.13 technical analyses. As part of this confirmation, reviewers should evaluate whether the most significant barriers, controls, or personnel that are relied upon for meeting the performance objectives are identified as defense-in-depth protections.

Reviewers should also confirm that the licensee has identified at least one redundant and one independent layer of defense, though there may be different layers that provide the redundancy and independence. Reviewers should confirm that the identification clearly associates a redundant layer with each primary layer of defense. A single layer may be able to perform a safety function that is redundant to several primary layers. As discussed in the next section, the safety function provided by the redundant layer would need to be comparable, but not identical, to the safety function provided by the primary layer and that often the designations of primary and secondary, or redundant, layers are in name only for the purposes of identification. Reviewers should also confirm that the licensee has identified which layers ensure independence. Independence should be assured for the disposal site as a whole. In other words, sufficient independence is demonstrated when common-cause failure scenarios are implausible or result in consequences that are acceptable. The next section also provides guidance on ensuring the safety functions for each independent layer are not subject to common-cause failures.

8.3.2 Description of Safety Functions

Licensees should describe the safety function(s) provided by each layer that is identified as a defense-in-depth protection for 10 CFR 61.13(f). Licensees should either qualitatively or quantitatively describe the capability of the individual layers identified to maintain safety. In addition, the description should include a technical basis supporting for the safety function. In general the technical basis supporting the safety function can be drawn from the technical basis used to support the layer's representation in the other 10 CFR 61.13 analyses. General guidance on developing support for the technical analyses is provided in Section 2.2, and specific guidance for each of the other 10 CFR 61.13 analyses is provided in their respective sections of this document.

Often, for a land disposal facility, the safety functions focus on (1) limiting the contact of water or individuals with the waste, (2) minimizing the release of radionuclides from the waste, or (3) minimizing the rate of radionuclide transport through the site environment. In addition, safety functions cover other considerations such as maintaining structural stability or limiting exposures to radioactivity. The safety function(s) may vary depending upon which performance objective the layer of defense is focused. In addition, a layer of defense may provide more than one safety function and these different safety functions may be aimed at providing confidence that different performance objectives will be met. Thus, licensees should clearly identify the capabilities the layer performs and the performance objective(s) the safety function is focused on in their description of the safety function for an individual layer.

If a layer of defense is included for redundancy, the licensee should clearly indicate other layers of defense the redundant layer is intended to support. Also, licensees should describe whether the safety function is independent or dependent upon the safety functions of other layers. If a layer's safety function is dependent upon another layer, the licensee should identify the other layer(s) in each layer's safety function description. If a layer's safety function is independent of other layers' safety functions, the licensee should provide justification that reasonably foreseeable and plausible common-cause failure scenarios would not result in significant consequences should they occur. Alternatively, licensees could identify additional layers of defense which would render the likelihood of the common-cause failure scenario as implausible.

Licensees should ensure that the description of the safety function is consistent with the representation of the layer of defense in the other 10 CFR 61.13 analyses. For instance, if a waste container is identified as a layer of defense aimed toward providing confidence that the performance objective for protection of the general population can be met, the description of its safety function should be consistent with its representation in the performance assessment. If the waste container is relied upon to limit water contacting waste and were to be modeled as degrading over time in the performance assessment, the licensee should identify the degradation of its safety function as part of the description for defense-in-depth.

In some cases, layers of defense may not be amenable to representation in one of the other 10 CFR 61.13 analyses. For instance, representing the response of personnel to an emergency such as a fire may not be amenable to representation in one of the other 10 CFR 61.13 analyses because the behavior of the personnel may vary depending upon the specific circumstance of the fire and would be difficult to simulate. In these cases, licensees would need to document the safety functions performed by the layers for demonstrating defense-in-depth.

For the emergency personnel example, this may include written procedures for training and emergency response, staffing plans, or agreements with local emergency responders.

Each layer of defense is likely to have a time period over which it will be designed to perform its intended safety function. For instance, the safety functions of engineered barriers would typically be expected to degrade and fail at some point in the future. However, some site characteristics may continue to provide safety functions indefinitely. The licensee should describe and justify this time period in its technical basis supporting the safety function of the layer. If the time period over which the layer is intended to perform its safety function significantly exceeds relevant experience, the licensee should provide additional support that the layer will likely achieve its goal. Additional support could include the use of additional redundant layers of defense, though support would be needed that the principal layer and any redundant layers in combination would perform the safety function over the intended time period.

Licensees should also describe the uncertainty in each layer's ability to perform its intended safety function and the time period over which it is expected to perform. The description of the uncertainty may be either qualitative or quantitative. The description of the uncertainty should be generally consistent with the layer's representation in the other 10 CFR 61.13 analyses. In describing the uncertainty associated with the safety function of a barrier, control, or personnel, licensees should identify heterogeneity and variability in the behavior or reliability of the barrier, control, or personnel as well as challenges to the functionality provided by a barrier, control, or personnel that result from plausible scenarios. Challenges should include both reasonably foreseeable scenarios expected during normal operations as well as less likely but plausible scenarios such as abnormal conditions, accidents, or disruptive events.

Reviewers should evaluate the description of the safety function of each layer to ensure that it clearly describes how the layer provides defense-in-depth protections and which performance objective the safety function supports. Reviewers should also confirm the description includes whether the safety function is included for redundancy, and whether the safety function is independent of or dependent upon another layer's safety function.

Reviewers should confirm that the safety function for a layer identified as redundant is clearly linked to the layer it is intended to support. Reviewers should confirm that the redundant layer's safety function provides a comparable capability to the primary layer's safety function. In some cases redundant layers that are identical to the primary layer are not possible. However, licensees could identify another barrier that may provide a comparable safety function. Reviewers should confirm that the safety functions are comparable. For instance, different hydrostratigraphic layers of the site may provide similar, but not identical safety functions. Likewise, an engineered barrier, such as a permeable reactive barrier, and a hydrostratigraphic layer of the site may both retard the movement of radionuclides as their safety functions. In this example, the safety functions are similar but the layers are not identical.

In addition to evaluating the licensee's basis for a redundant safety function, reviewers should also evaluate whether the layers identified as independent are subject to common-cause failures based on reasonably foreseeable as well as less likely, but plausible scenarios. Plausible common-cause failures may result from a common initiating event such as a seismic event that fails two barriers simultaneously. Plausible common-cause failures may also result from a cascade of processes such as when a geochemical environment leads to the degradation of a barrier whose degradation produces an environment that leads to the degradation of a different barrier, which may not have been affected by the initial aggressive environment.

Reviewers should also confirm the licensee's safety function descriptions include a discussion of the time period over which the layer's safety function is intended to perform and the uncertainty in whether the layer can perform the safety function. For layers of defense which are expected to perform for time periods that significantly exceed relevant experience, reviewers should confirm that the licensee has provided sufficient justification. Reviewers should also coordinate the review of the safety function descriptions with reviews of the other 10 CFR 61.13 analyses to ensure that the layers and their safety functions are implemented in those other analyses consistent with the licensee's description of the safety function for defense-in-depth. If redundant layers are expected to perform over different time periods than the primary layers, reviewers should confirm that the licensee has identified other layers to ensure that redundancy is provided for the entire time period of interest or that the consequences would remain acceptable should redundancy not be possible for the entire time period of interest.

Reviewers should also confirm the licensee has included a description of the uncertainty in each layer's ability to perform its intended safety function and the time period over which it is expected to perform as part of the safety function description. Reviewers should coordinate their review of the description of uncertainty with the reviews of the other 10 CFR 61.13 analyses to ensure that the uncertainty descriptions are generally consistent and describe the heterogeneity and variability in the behavior or reliability of the barrier, control, or personnel as well as challenges to the functionality provided by a barrier, control, or personnel that result from plausible scenarios.

8.3.3 Demonstrating Safety Margin

After describing the safety function provided by each layer identified as a defense-in-depth protection, licensees should demonstrate that the layers will maintain safety and that no single layer will be relied upon exclusively for safety. The level of detail provided by the licensee in describing the technical basis should be risk-informed. Namely, for layers of defense that provide one or more significant safety functions, licensees should provide a more detailed description of the basis for the safety function provided by the layer of defense.

Licensees can use a variety of methods to demonstrate that safety functions will perform adequately and that no single layer will be relied upon for safety in light of the uncertainties in the performance of the layers and the evolution of the disposal site over long periods of time such as those associated with the post-closure period. Generally, the methods may be quantitative, qualitative, or a combination of the two approaches. Quantitative approaches attempt to assign numerical values to the safety functions and the resulting safety margin provided by the layers of defense relied upon for safety. Qualitative approaches are less numerical and narratively describe the safety functions and the resulting safety margin of the various layers of defense relied upon for safety.

Licensees may use different approaches to demonstrate layers of defense for different stages or even within a stage of the land disposal facility's lifecycle. For instance, while some layers of defense used during operations may be amenable to quantification other layers of defense may not be, such as the safety margin provided by an emergency response plan to mitigate the consequences of an accident. Typically, licensees should be able to use the results of the other 10 CFR 61.13 analyses to demonstrate that the layers will ensure the performance objectives are met for reasonably foreseeable scenarios and that the consequences from less likely but plausible scenarios would not be so large to require intervention if they were to occur today. For instance, for the post-closure period, licensees should draw risk insights from the performance assessment (see Section 3.0), intruder assessment (see Section 4.0), and site-stability analyses (see Section 5.0) to demonstrate that no single layer is relied upon exclusively for safety over the various time periods.

Rather than developing new analyses, licensees may use uncertainty analyses conducted for the other 10 CFR 61.13 analyses such as barrier analyses, including one-off or what-if types of analyses, to demonstrate adequate independence and redundancy is provided and that no single layer is relied upon for safety for both reasonably foreseeable and less likely, but plausible scenarios over the time period of interest. The results of these uncertainty analyses can be used to demonstrate that if any single barrier fails during the time period of interest, another barrier is available to provide a similar and adequate level of protection. The results of the other 10 CFR 61.13 analyses can also be used to demonstrate that common-cause failures would not result from reasonably foreseeable or less likely, but plausible scenarios or if common-cause failure were to occur for plausible scenarios, the consequences would not be so large as to require intervention today. Barrier analyses are described in more detail in Section 7.4 for analyses for long-lived waste. Although the description in Section 7.4 relates to performance period analyses, the barrier analysis techniques are also generally appropriate for any of the post-closure time periods of interest. Consequences that may require intervention today are discussed in the following sections for each time period with due consideration for the uncertainty associated with projecting safety functions, human activities, and the behavior of the disposal site environment far into the future.

The lifecycle of a land disposal facility can be divided into two broad phases: the operational phase and the post-closure phase. The operational phase is the time period during which the facility is being constructed, is receiving waste for disposal, or is preparing for closure. The post-closure phase extends from the cessation of operations far into the future depending upon the type of waste accepted for disposal. At a minimum the post-closure phase would include the compliance and protective assurance periods. For facilities disposing of significant quantities of long-lived waste, the post-closure phase would also include the performance period. Because of the differences in length of the time periods for the operational and post-closure phases, the role of defense-in-depth analyses may be markedly different for each phase.

The following two sections describe considerations for licensees and reviewers for the two major lifecycle phases of a land disposal facility and guidance on demonstrating a land disposal facility's safety margin provided by the defense-in-depth protections and demonstrating that no single layer, not matter how robust, will be exclusively relied upon for safety.

8.3.3.1 *Operational Period*

During the operational phase of the land disposal facility, defense-in-depth protections may be similar to those used at other nuclear facilities that present similar hazards. Defense-in-depth protections during operations may include, but are not limited to: (1) the selection and use of facility capabilities, such as functions, structures, systems, and components of the facility design; (2) programmatic processes, such as decisions regarding the processes of constructing, operating, maintaining, testing, and inspecting the plant, as well as processes that ensure facility safety through its operational lifetime; and (3) risk-informed strategies that manage the risks of accidents, including the strategies of accident prevention and mitigation.

During the operational period, licensees can draw upon risk insights gained from the analyses used to demonstrate compliance with the performance objectives for operations including protection of the general population, protection of inadvertent intruders, and protection of individuals during operations (i.e., 10 CFR 61.41 through 10 CFR 61.43) to demonstrate that defense-in-depth protections are included. The defense-in-depth analyses for an operating land disposal facilty are expected to be similar to demonstrations of defense-in-depth for other operating facilities that use radioactive materials (e.g., nuclear reactors). For instance, the land disposal facility would use procedures and engineering controls as part of a radiation control program, required by 10 CFR 20.1101, to minimize occupational doses and doses to members of the public. In this example, the licensee would need to identify the specific procedures and controls that are relied upon for safety should plausible scenarios that challenge safety functions occur, describe the safety functions associated with the procedures and controls and when those safety functions are expected to be necessary, as well as describe the uncertainty in the safety functions to perform adequately.

Licensees can use the results of analyses that are similar to those used at other nuclear facilities (e.g., an integrated safety analysis as described in NUREG-1513 (NRC, 2001) for licensing of special nuclear material) to demonstrate that no single layer of defense will be exclusively relied upon for safety at an operating land disposal facility. The amount of detail needed for a land disposal facility may be markedly different than for other facilities depending upon the hazards present and the risks involved in the use of the radioactive material at the disposal facility or the handling of waste for disposal.

Licensees should examine whether the layers of defense, their associated safety functions, and uncertainty ensure safety during operations by limiting the likelihood or consequences during reasonably foreseeable and less likely, but plausible scenarios. For facilities or activities with more significant hazards (e.g., emplacement of high activity waste), which could result in significant potential exposures to workers or the public during operations, additional redundancy and a stronger basis for independence among the layers may be necessary. Reviewers should consider potential exposures from plausible scenarios during operations of a land disposal facility as significant for the purposes of defense-in-depth when they are expected to exceed the occupational dose limits or the dose limits for members of the public specified in 10 CFR Part 20, Subparts C and D, respectively. For plausible scenarios with significant exposures, licensees should consider additional layers of defense, further redundancy, improved independence, or reduced uncertainty in the safety function of the layers to ensure that the likelihood of significant exposures is reduced so that the scenario becomes implausible or that the consequences are sufficiently reduced.

8.3.3.2 *Post-Closure Period*

Following closure of the land disposal facility, defense-in-depth protections shift from a collection of active and passive barriers and controls that are used during operations to reliance on controls and passive barriers. Defense-in-depth protections for the post-closure period may include, but are not limited to, engineered features (e.g., closure caps, wasteforms, and containers) and natural characteristics (e.g., hydrogeology) of the disposal site that are intended to contain and isolate the waste, as well as controls such as institutional controls, which are designed to limit access to the disposal site for a limited period of time, and waste acceptance requirements, which are designed to limit the radionuclide inventory in the disposal site.

As a result of increasing uncertainty in the behavior of the layers of defense, particularly barriers, and the disposal site environment, the associated uncertainty in the margin of safety provided by the layers of defense is also expected to increase. In addition to the barriers themselves, licensees may also need to consider additional controls to ensure that the barriers relied upon for safety will perform adequately. These controls may include quality assurance controls during the design, construction, operation, and maintenance of engineered barriers (e.g., engineered closure caps, wasteforms, or containers) or, more importantly, given the long timeframes involved, additional inventory controls to limit the amount of waste disposed at the disposal site. Development of waste acceptance criteria is described further in Section 9.0.

For the post-closure period, licensees can draw upon risk insights gained from the results of the other 10 CFR 61.13 post-closure analyses (i.e., performance assessment, intruder assessment, and stability analyses) rather than developing specific analyses for demonstrating that defense-in-depth protections are included. Those other 10 CFR 61.13 analyses are expected to focus on protections that can maintain safety, in the context of the post-closure performance objectives, for the disposed waste over the various regulatory time periods that are pertinent. The post-closure period is subdivided into three timeframes: the compliance period, the protective assurance period, and the performance period. Depending upon the waste received, the performance period may not apply to the land disposal facility and defense-in-depth analyses may not be needed for the longer-term period (i.e., analyses that extend beyond 10,000 years). Because 10 CFR Part 61 does not envision ongoing active maintenance and monitoring at the disposal site, the layers of defense for these three time periods are expected to be primarily barriers and inventory limits after 100 years following closure, when the institutional controls are assumed to no longer be effective.

Licensees can use results from the uncertainty analyses performed for the other 10 CFR 61.13 analyses to demonstrate that adequate defense-in-depth protections are included. For instance, Section 7.4 describes how to conduct barrier analyses for demonstrating compliance during the performance period. Barrier analyses are common uncertainty analyses performed as part of a performance assessment, and though the guidance in Section 7.4 is focused on the performance period, it is generally applicable to conducting barrier analyses for any of the post-closure time periods. By examining the consequences of early degradation or failure of one or more of the layers of defense, licensees can demonstrate that safety can be maintained or determine that additional layers of defense, further redundancy, improved independence, or reduced uncertainty in the safety function of a layer may be needed.

To demonstrate that the layers of defense are adequate, licensees should examine not only the reasonably foreseeable scenarios considered for demonstrating that the performance objectives would be met, but also less likely, but plausible scenarios (e.g., accidents, disruptive events, abnormal occurrences). If the performance objectives are met, significant consequences are generally not expected for reasonably foreseeable scenarios. However, significant consequences may be possible for less likely, but plausible scenarios. The following sections provide guidance on when additional layers of defense, further redundancy, improved independence, or reduced uncertainty in the safety function of a layer may be needed to demonstrate that adequate defense-in-depth protections are included for each of the three post-closure time periods.

8.3.3.2.1 Compliance Period

During the compliance period, uncertainty in the behavior of the layers of defense and the evolution of the disposal site environment at a well-sited disposal facility is expected to be more manageable than for longer time periods. In terms of the disposal site and design, licensees should demonstrate that the margin of safety determined by the layers of defense provides confidence that the limits specified in 10 CFR 61.41(a) and 10 CFR 61.42(a) are not expected to be exceeded for the central scenario. To demonstrate that an adequate margin of safety is available, licensees could compare probabilistic dose curves derived from the analyses used to demonstrate that the performance objectives are met below the designated limit. At a minimum, unless otherwise authorized, licensees must demonstrate that the specified limit is not exceeded for the mean doses during the compliance period to demonstrate that the performance objectives are met. If the peak of the mean dose curve exceeds the specified limit, then additional layers of defense or added redundancy are necessary for engineering design of the facility or the disposal site to be appropriate for disposal. Guidance on demonstrating that the performance objectives are met is described in Section 3.0 for protection of the general population and Section 4.0 for protection of inadvertent intruders. Guidance on demonstrating the long-term stability of the disposal site is discussed in Section 5.0.

Once licensees demonstrate that the performance objectives are met, they should demonstrate that an adequate margin of safety is provided by the layers of defense such that significant exposures, which would require future intervention to mitigate, would not be expected to occur. To do this, licensees should demonstrate that the 95th percentile of annual doses from probabilistic analyses of the central scenario at each discrete time during the compliance period is less than the dose limits for members of the public (i.e., 1 mSv [100 mrem]), as described in Section 3.2.4.3 of NUREG-1573 (NRC, 2000a), and less than 20 mSv (2 rem) for protection of inadvertent intruders, an exposure level for human intruders above which alternative options for waste disposal are to be considered (IAEA, 2011).

Additionally, if the peak annual dose from any single or subset of realizations of the central or alternative scenarios exceeds 50 mSv (5 rem) for either protection of the general population or inadvertent intruders, licensees should examine those realizations (or alternative scenarios) to determine whether additional layers of defense, independence, or redundancy would be beneficial. The 50 mSv (5 rem) guidance threshold provides confidence that any plausible projected scenario would not be expected to exceed a level that would almost always justify intervention in an emergency situation. The ICRP advises that intervention would almost always be justified for existing exposures that would exceed 100 mSv (10 rem) (ICRP, 2007). In this case, additional layers of defense, independence or redundancy should ensure that doses for any plausible scenario are maintained well below levels where future intervention to mitigate significant exposures would be necessary or that the likelihood of the realization would be reduced by the additional layers of defense to render it implausible.

If a licensee performs deterministic rather than probabilistic analyses, the licensee should demonstrate that all annual doses from reasonably foreseeable or less likely, but plausible scenarios are less than 1 mSv (100 mrem) for protection of the public and less than 20 mSv (2 rem) for protection of inadvertent intruders, in order to ensure doses would be maintained well below levels where future intervention to mitigate significant exposures would be necessary.

Disposal facilities that could result in potential doses from reasonably foreseeable or less likely but plausible scenarios that exceed those mentioned in the previous paragraphs during the compliance period are considered higher-risk disposal facilities. Licensees should employ additional layers of protection or ensure that sufficient independence and redundancy will be provided to ensure that common-cause failures are minimized and adequate redundancy in the safety function is provided so that a significant exposure is highly unlikely to occur.

8.3.3.2.2 Protective Assurance Period

During the protective assurance period, uncertainty in the behavior of the layers of defense and the evolution of the disposal site environment is expected to increase, due to lack of knowledge about the key properties of the layers of defense and the disposal site environment, as well as FEPs and human activities that may occur in the future at or near the disposal site. In terms of the disposal site and design, licensees should demonstrate that the margin of safety determined by the layers of defense provides confidence that the exposures will be below a reasonably achievable level, as required in 10 CFR 61.41(b) and 10 CFR 61.42(b), for the central scenario. The performance objectives for the protective assurance period require the minimization of exposures, with a goal of limiting the annual dose below 5 mSv (500 mrem) or a level that is reasonably achievable based on technological and economic considerations. Therefore, at a minimum, licensees must demonstrate that the specified minimization goal for the disposal site is met. If the minimization goal is not met, licensees would need to add additional barriers or impose additional controls to demonstrate that the minimization goal will be met. Guidance on developing minimization targets and demonstrating that minimization is met is provided in Section 6.0.

Once licensees demonstrate that the performance objectives are met, licensees should demonstrate that an adequate margin of safety is provided by the layers of defense for the protective assurance period such that significant consequences are minimized for plausible scenarios. Licensees should be able to draw risk insights from the results of the performance assessment (see Section 3.0), intruder assessment (see Section 4.0), and site stability analyses (see Section 5.0) to estimate safety functions and their associated uncertainty during the protective assurance period.

To demonstrate that an adequate margin of safety is provided for the protective assurance period, licensees should demonstrate that the layers of defense maintain the peak annual dose from any single or subset of realizations (or from a less likely, but plausible alternative scenario for a deterministic analyses) below 50 mSv (5 rem) for either protection of the general population or inadvertent intruders. The 50 mSv (5 rem) guidance threshold provides confidence that any plausible projected scenario would not be expected to exceed a level that would almost always justify intervention in an emergency situation. The ICRP advises that intervention would almost always be justified for existing exposures that would exceed 100 mSv (10 rem) (ICRP, 2007). Disposal facilities that could result in potential doses from reasonably foreseeable or less likely, but plausible scenarios that exceed 50 mSv (5 rem) during the protective assurance period are considered higher-risk disposal facilities.

At higher-risk facilities, licensees should employ additional layers of protection or ensure that sufficient independence and redundancy will be provided to ensure that common-cause failures are minimized and adequate redundancy in the safety function is provided so that a significant exposure is highly unlikely to occur. In deciding whether additional layers of defense would be needed, licensees may consider technological or economic limitations to employing additional barriers. However, the additional cost of limiting inventory is typically not expected to be overly burdensome from either a technical or economic consideration and is expected to provide the greatest certainty that the performance objectives can be met. Therefore, licensees and reviewers should strongly consider additional inventory limits as added controls or alternative siting to ensure the performance of the existing barriers when other additional layers of defense may not be practical for technological or economic reasons.

8.3.3.2.3 Performance Period

During the performance period, uncertainty in the behavior of the layers of defense and the evolution of the disposal site environment is expected to be significantly larger than other analysis time periods. The increased uncertainty is due to lack of knowledge about the key properties of the layers of defense and the disposal site environment as well as FEPs and human activities that may occur in the future at or near the disposal site. As a result of increasing uncertainty in FEPs that could be expected to occur, the associated uncertainty in the margin of safety provided by the layers of defense is also expected to increase.

In terms of the disposal site and design, licensees should demonstrate that the the layers of defense provide confidence that releases and exposures will be minimized to the extent reasonably achievable, as specified in 10 CFR 61.41(c) and 10 CFR 61.42(c), respectively. Guidance on developing demonstrating that minimization is met for the performance period is provided in Section 7.0.

Once licensees demonstrate that the performance objectives are met, licensees should demonstrate that an adequate margin of safety is provided by the layers of defense for the performance period such that significant consequences are minimized for plausible scenarios. To demonstrate that an adequate margin of safety is maintained during the performance period, licensees should demonstrate that the layers of defense maintain releases from the disposal site that result in exposures to the general population or exposures to an inadvertent intruder at or below 50 mSv (5 rem). The 50 mSv (5 rem) guidance threshold provides confidence that any plausible projected scenario would not be expected to exceed a level that would almost always justify intervention in an emergency situation. The ICRP advises that intervention would almost always be justified for existing exposures that would exceed 100 mSv (10 rem) (ICRP, 2007). Disposal facilities that could result in potential doses that exceed 50 mSv (5 rem) for plausible scenarios during the performance period are considered higher-risk disposal facilities. Licensees may also be able to develop alternative measures of safety margin. For instance, licensees could compare concentrations in media to concentrations that would require intervention today should a less likely, but plausible scenario occur.

Disposal facilities that could result in potential doses from reasonably foreseeable or less likely but plausible scenarios that exceed those mentioned in the previous paragraphs during the compliance period are considered higher-risk disposal facilities. Licensees should employ additional layers of protection or ensure that sufficient independence and redundancy will be provided for the disposal site to ensure that common-cause failures are minimized and adequate redundancy in the safety function is provided so that a significant exposure is highly unlikely to occur.

In deciding whether additional layers of defense would be needed, licensees may consider technological or economic limitations to employing additional barriers. However, the additional cost of limiting inventory is typically not expected to be overly burdensome from either a technical or economic consideration and is expected to provide the greatest certainty that the performance objectives can be met. Therefore, licensees and reviewers should strongly consider additional inventory limits as added controls or alternative siting to ensure the performance of the existing barriers when other additional layers of defense may not be practical for technological or economic reasons.

9.0 WASTE ACCEPTANCE

Section 61.23 of 10 CFR Part 61 specifies standards that must be met to receive a license to operate a land disposal facility for LLW. The standards require licensees to demonstrate that the waste acceptance criteria and other components of the licensee's proposal are adequate to protect public health and safety and provide reasonable assurance that the performance objectives specified in Subpart C will be met. The regulations at 10 CFR 61.58 specify the requirements for waste acceptance. The regulations require licensees to identify (i) criteria for the acceptance of waste for disposal, (ii) acceptable methods for characterizing the waste, and (iii) a program to certify that waste meets the acceptance criteria prior to receipt at a land disposal facility for radioactive waste. Figure 9-1 illustrates the main components of waste acceptance under 10 CFR Part 61. The regulations also require licensees to review the content and implementation of the waste acceptance criteria, characterization methods, and certification program at least annually.

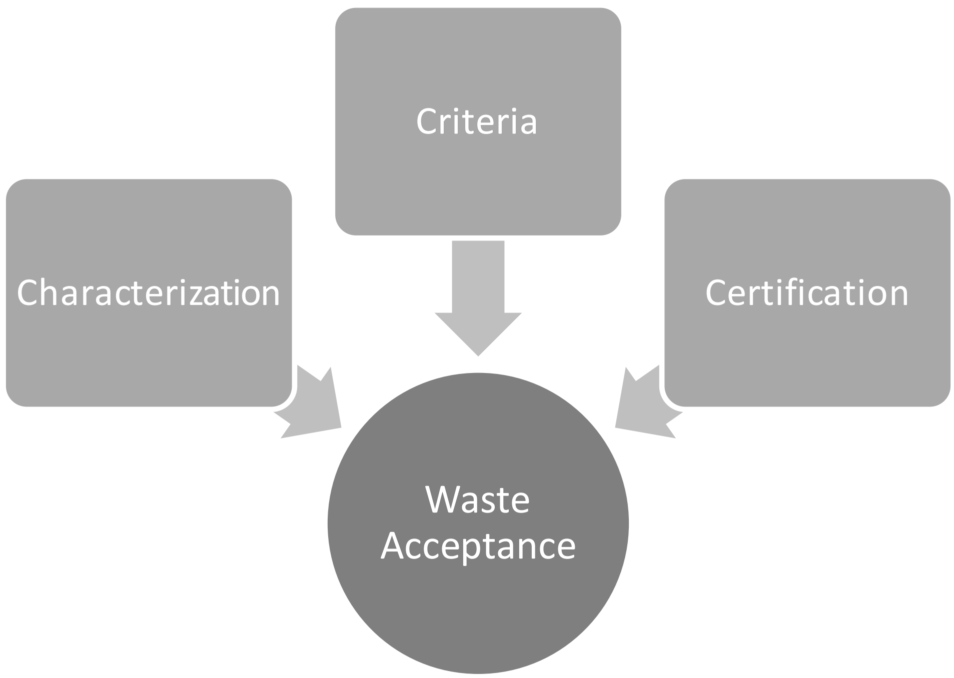

Figure 9-1 Waste Acceptance Components

This section describes the information that a licensee should provide and a reviewer should evaluate with respect to the waste acceptance requirements. First, the waste acceptance criteria identify the following for waste generators: (1) the allowable limits on radionuclides, (2) acceptable wasteforms and container specifications, and (3) restrictions or prohibitions in order for waste to be accepted for disposal as LLW. Section 9.1 describes information that licensees should provide to demonstrate that the waste acceptance criteria will be adequate. Second, in order to demonstrate that the waste meets the acceptance criteria, waste must be adequately characterized. Section 9.2 provides guidance to licensees on defining acceptable methods for waste characterization. Finally, waste must be certified to ensure that waste meets the acceptance criteria and is, therefore, suitable for disposal in a land disposal facility. Section 9.3 describes information that licensees should include in a certification program to ensure that waste received at the disposal facility is acceptable for disposal.

9.1 Waste Acceptance Criteria

Section 61.52 of 10 CFR Part 61 requires that all waste disposed in the disposal site must meet approved waste acceptance criteria. Section 61.58 of 10 CFR Part 61 requires licensees to submit proposed waste acceptance criteria for approval. Once the disposal site regulator approves the waste acceptance criteria, licensees wishing to make modifications to the criteria must request an amendment. This section provides guidance on developing or modifying waste acceptance criteria and discusses information that licensees should include in order to allow a regulator to evaluate whether the proposed waste acceptance criteria provide reasonable assurance that the performance objectives will be met.

Figure 9-2 Components of 10 CFR Part 61 Waste Acceptance Criteria

Section 61.58 of 10 CFR Part 61 specifies the requirements for waste acceptance at a disposal facility for LLW. Waste acceptance criteria are intended to provide reasonable assurance that the performance objectives of 10 CFR Part 61 will be met. The regulations require licensees to identify the criteria for the acceptance of waste for disposal (i.e., waste acceptance criteria). Specifically, the regulations require that the waste acceptance criteria specify, at a minimum, allowable activities and concentrations of specific radionuclides, acceptable wasteform characteristics and container specifications, and restrictions or prohibitions on waste, materials, or containers. Figure 9-2 depicts the minimum components of the waste acceptance criteria.

Licensees may need to specify other criteria beyond those required by 10 CFR Part 61 to satisfy other regulatory requirements. For instance, land disposal facilities may also be required by other Federal or State regulations to limit certain non-radiological materials because of their impact on public health and safety and the environment. This guidance document focuses only on the waste acceptance criteria required by 10 CFR Part 61.

9.1.1 Allowable Activities and Concentrations

The waste acceptance requirements of 10 CFR Part 61 allow licensees the option to develop allowable limits from either the technical analyses required in 10 CFR 61.13 for any land disposal facility or the waste classification limits in 10 CFR 61.55 for a near-surface disposal facility. For instance, licensees disposing of waste that is similar to the waste streams considered in the development of the waste classification limits may wish to rely on those limits.

Whereas, licensees disposing of waste streams beyond those considered for the waste classification requirements may wish to determine limits from the results of their technical analyses. Likewise, licensees with facility designs, operational practices, or site characteristics that differ significantly from those considered to develop the waste classification limits, may also wish to develop site-specific waste acceptance criteria. The unique characteristics of the waste in concert with the disposal site and design are the primary determinants of risk from near-surface disposal. Thus, not all radioactive waste streams may be suitable for near-surface disposal.

This section of the guidance document describes the information that a licensee should provide and that a reviewer should evaluate with respect to the development of allowable activities and concentrations for radionuclides. Reviewers may want to consult Standard Review Plan 6.1.1 of NUREG-1200 (NRC, 1994) to ensure that the allowable limits specified by the licensee's waste acceptance criteria are reasonable, given the types and quantities of radionuclides projected for disposal.

9.1.1.1 *Allowable Limits Derived from Technical Analyses*

Radioactivity disposed in a land disposal facility may need to be limited to ensure (i) protection of the general public from releases during operations and after operations have ceased, (ii) protection of individuals who may inadvertently intrude into the disposal site after active institutional controls are removed, (iii) protection of individuals during operations, and (iv) stability of the disposal site after closure. Limits on radioactivity disposed in a land disposal facility can also provide defense-in-depth. The limits may vary widely from site-to-site depending on the waste streams proposed for disposal, facility design, and site characteristics.

Licensees who elect to develop limits on radionuclide activities or concentrations from the results of the analyses required in 10 CFR 61.13 should document how the proposed limits are developed from the analyses performed to satisfy the requirements of 10 CFR 61.13. The proposed limits should focus on radionuclides that may affect meeting the performance objectives. These limits may be unique for specific waste streams or total limits for the disposal site. Proposed limits for specific waste streams may be more appropriate when unique factors may affect meeting one or more of the 10 CFR Part 61 performance objectives such as the anticipated release from a particular wasteform, the concentrations of radionuclides in the waste, the potential for criticality due to the presence of special nuclear material in the waste, the radiation fields emanating from the waste, or the heat generated by the decaying waste.

Licensees should develop allowable limits, either total activity or concentration, from the resulting peak doses from a unit activity of each radionuclide for the performance objective which is the most limiting for each radionuclide. When evaluating each performance objective, the licensee should use the scenario(s) used to demonstrate that the performance objectives are met to establish the limits. Selection of the scenario(s) for demonstrating compliance with the performance objectives is described in Sections 2.0, 3.0, and 4.0 of this document. To develop limits, licensees should compare the peak dose for each radionuclide with the limits specified by the performance objective.

Licensees may calculate a limit for each radionuclide using:

$$Limit_{i,s} = \frac{Dose\ Limit_s \times Activity(0)_i}{Peak\ Dose_{i,s}} \qquad (9.1)$$

where

$Limit_{i,s}$	is the total activity [Bq] or activity concentration [Bq/m^3 or Bq/g] limit of radionuclide *i* in waste for scenario *s*;
Dose $Limit_s$	is the dose limit [mSv/yr] for scenario *s*;
$Activity(0)_i$	is the initial total activity [Bq] or activity concentration [Bq/m^3 or Bq/g] of radionuclide *i* in the waste; and
Peak $Dose_{i,s}$	is the annual peak dose [mSv/yr] resulting from the $Activity(0)_i$ of radionuclide *i* for scenario *s*.

Licensees should clearly identify the technical basis for each allowable limit specified in the waste acceptance criteria. The basis for each proposed limit should include the performance objective(s) that the limits are designed to support. For instance, proposed limits for some radionuclides may be more relevant to protection of facility workers during operations than to protection of the general public from releases. The basis should also emphasize why each proposed limit is sufficient to demonstrate that the performance objectives will be met. Licensees will also need to demonstrate that the individual limits, when taken together, will ensure that the performance objectives continue to be met.

Licensees should describe in the technical basis supporting the allowable limits how they account for variability and uncertainty in anticipated inventories when developing the allowable limits. One method to mitigate uncertainty is to manage it through controls or restrictions. A key control to account for variability and uncertainty is imposing limits on the radionuclide inventory of disposed waste. The inventory of radionuclides in the waste disposed can be readily controlled, whereas uncertainty associated with the natural system or engineered barriers, for example, may be difficult to define or, if understood, difficult to reduce. The following general guidelines are useful for the development of allowable limits under 10 CFR 61.58:

- Allowable limits should be established conservatively so as to reduce the need for future mitigation.
- The analysis used to develop allowable limits should be as complete as practicable and include uncertainties.

The allowable limits will be affected by the complexity of the disposal site and its environment, the conservatism in the analyses, and the amount of information available to support the assessment. Figure 9-3 provides the relative change in the safety factor with changes in the relative value of these variables. For example, when the amount of information available to support the analyses is relatively large, licensees may apply a small margin of safety to the results of the analyses to establish the limits. On the other hand, if the disposal site environment is complex, licensees may need to apply a large margin of safety in order to provide reasonable assurance the performance objectives will be met. In other words, the uncertainty in the risk will be a primary driver of the values for the limits. There is no absolute value (e.g., an inventory that corresponds to 10 percent of the 0.25 mSv/yr or 25 mrem/yr dose limit) that is appropriate to use to establish limits for all sites. Allowable limits can be viewed as one of several safety factors or defense-in-depth protections used to mitigate uncertainty in other (i.e., non-inventory) areas of the technical analyses.

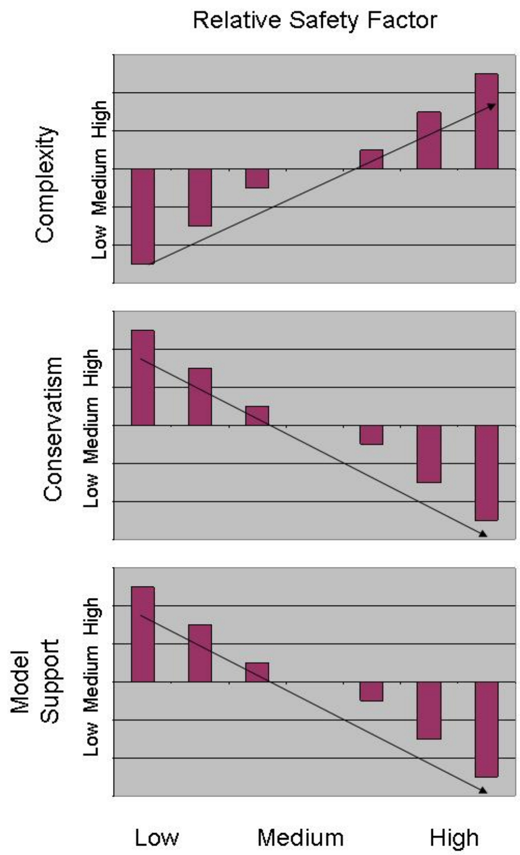

Figure 9-3 Influence of Key Variables on the Required Relative Safety Factors

Reviewers should coordinate reviews of the allowable limits with the reviews of the technical analyses required to meet 10 CFR 61.13 (see Sections 3.0, 4.3, and 8.0 of this document). Reviewers should verify that the licensee's proposed limits on activities and concentrations are adequate, considering the source term inventory used in the performance and intruder assessments as well as assessments of expected and accidental occupational exposures during handling, storage, and disposal of waste.

In general, the proposed limits should be consistent with the source term evaluated in the technical analyses. However, licensees may use a variety of approaches to develop allowable limits. For example, a licensee may derive a limit from the results of one or more of the analyses for a source term with a unit concentration (e.g., 1.0 nCi/g) that is then scaled to the limit specified by the relevant performance objective. In this example, the proposed limits would not be expected to be consistent with the source term employed in the analyses. Rather, the limits should be consistent with the outcome of the analyses that meets the performance objective. Regardless of the approach, the reviewer should evaluate whether the approach is appropriate. Assuming a source term with unit concentrations of disposed waste may not be appropriate in circumstances where the radiological exposures are non-linearly correlated to source term concentrations.

Reviewers should also assess the spatial extent and distribution of the radionuclide inventory evaluated in the analyses to determine whether the allowable proposed limits are appropriate (e.g., when considering the disposal facility's operating procedures for emplacement). In some cases, depending on the scenarios evaluated in the technical analyses to demonstrate the performance objectives are met, the spatial extent or distribution of radionuclide inventory in the disposal site may also need to be controlled as an allowable limit. For example, a licensee develops a total average activity concentration limit for a particular radionuclide from the intruder assessment based on an expected volume to which the intruder may be inadvertently exposed. Reviewers should confirm that the facility's operating procedures would reasonably ensure that the proposed limit would not be expected to be exceeded for any volume of the disposal unit equivalent to the intrusion volume assumed by the licensee in the assessment.

Reviewers should evaluate how stability is considered when establishing the allowable limits. First, stable wasteforms or containers may allow the disposal of waste with higher radioactivity than unstable waste. Therefore, reviewers should evaluate the estimated performance of the wasteforms, containers, or other design features that provide stability. Reviewers should coordinate this review with the review of acceptable wasteforms and containers, which is described Section 9.1.2 of this document. Reviewers should confirm that licensees are establishing waste acceptance criteria for wasteforms, containers, or design features that provide assurance the expected performance can be achieved. Second, there may be cases where the radionuclide inventory could significantly affect the stability of the disposal site after closure. For example, reviewers may need to evaluate whether radiation fields or thermal output from radioactive decay for certain higher activity waste streams would significantly compromise structural stability of the waste containers or degradation of the wasteforms and lead to stability issues for the disposal unit. Reviewers should coordinate their review of the development of allowable limits from the technical analyses with their review of acceptable wasteform characteristics and container specifications (see Section 9.1.2).

In general, reviewers should focus their review of allowable limits on those radionuclides expected to contribute most significantly to risk to the public, workers, and the environment. Typically, radionuclides with relatively high solubility, low sorption, high dose conversion factors, and/or significant in-growth are of particular significance. However, the importance of radionuclides may vary based upon the specific performance objective under consideration. For instance, non-mobile radionuclides may be more significant for protection of inadvertent intruders.

Reviewers should also evaluate whether the technical basis provided for each proposed limit will provide assurance that all the performance objectives will be met. For example, if an allowable limit is set for a particular radionuclide based on the results of the performance assessment, reviewers should confirm that the limit would not preclude licensees from demonstrating that the other performance objectives (e.g., protection of inadvertent intruders via the intruder assessment) are met. This review should also ensure that the allowable limits are comprehensive and that all necessary limits are included. Reviewers may elect to conduct independent analyses to inform the review.

9.1.1.2 *Allowable Limits Derived from Waste Classification*

Licensees who elect to develop allowable limits for radionuclides from the 10 CFR Part 61 waste classification requirements may simply report the concentration limits reported in 10 CFR 61.55. The limits specified in 10 CFR 61.55 shall be applied on a per package basis. Licensees may also need to develop alternative limits for radionuclides not listed in the tables, particularly for waste that is significantly different than what was considered in the analyses used to develop the tables (see NRC, 1981a). Tables 4.1 and 4.2 of NUREG-0945, Volume 1 (NRC, 1982b) list the waste streams and radionuclides considered in the analyses to develop the tables. Guidance on developing limits on radionuclides not listed in the waste classification tables is also provided in this section.

The concentration limits reported in 10 CFR 61.55, together with the requirements for waste characteristics, 10 CFR 61.56, and segregation, 10 CFR 61.52(a)(1) and (2), provide reasonable assurance that an intruder would be protected should they inadvertently be exposed to the waste that has been disposed in a facility. Classification involves consideration of both (1) long-lived radionuclides, whose potential hazard will persist long after precautions such as institutional controls, improved wasteform, and deeper disposal have ceased to be effective; and (2) shorter-lived radionuclides, for which such precautions can be effective.

Classification is also used to determine which waste characteristics requirements in 10 CFR 61.56 are necessary. Further, classification is used to determine the waste segregation requirements in 10 CFR 61.52 that the disposal facility must meet during operations. Waste segregation provides assurance that waste is disposed of in a manner that limits potential exposures, including those to an inadvertent intruder, based on the hazard and stability of the waste. Figure 9-4 illustrates the waste classification and segregation requirements for LLW. Thus, licensees relying on the waste classification system to develop allowable limits must also ensure that criteria for both acceptable wasteform characteristics and facility operating practices are consistent with the related requirements for waste characteristics and segregation. Further guidance on developing criteria for acceptable wasteform characteristics is provided in Section 9.1.2 of this document.

Licensees can demonstrate compliance with the classification requirements for selected radionuclides by comparing radionuclide concentrations in LLW to the values listed in the tables of long- and short-lived radionuclides in 10 CFR 61.55. The radionuclide concentrations listed in the classification tables were developed, in part, from two considerations: direct contact with the disposed waste (i.e., intrusion) and potential consumption or use of contaminated groundwater (i.e., migration).

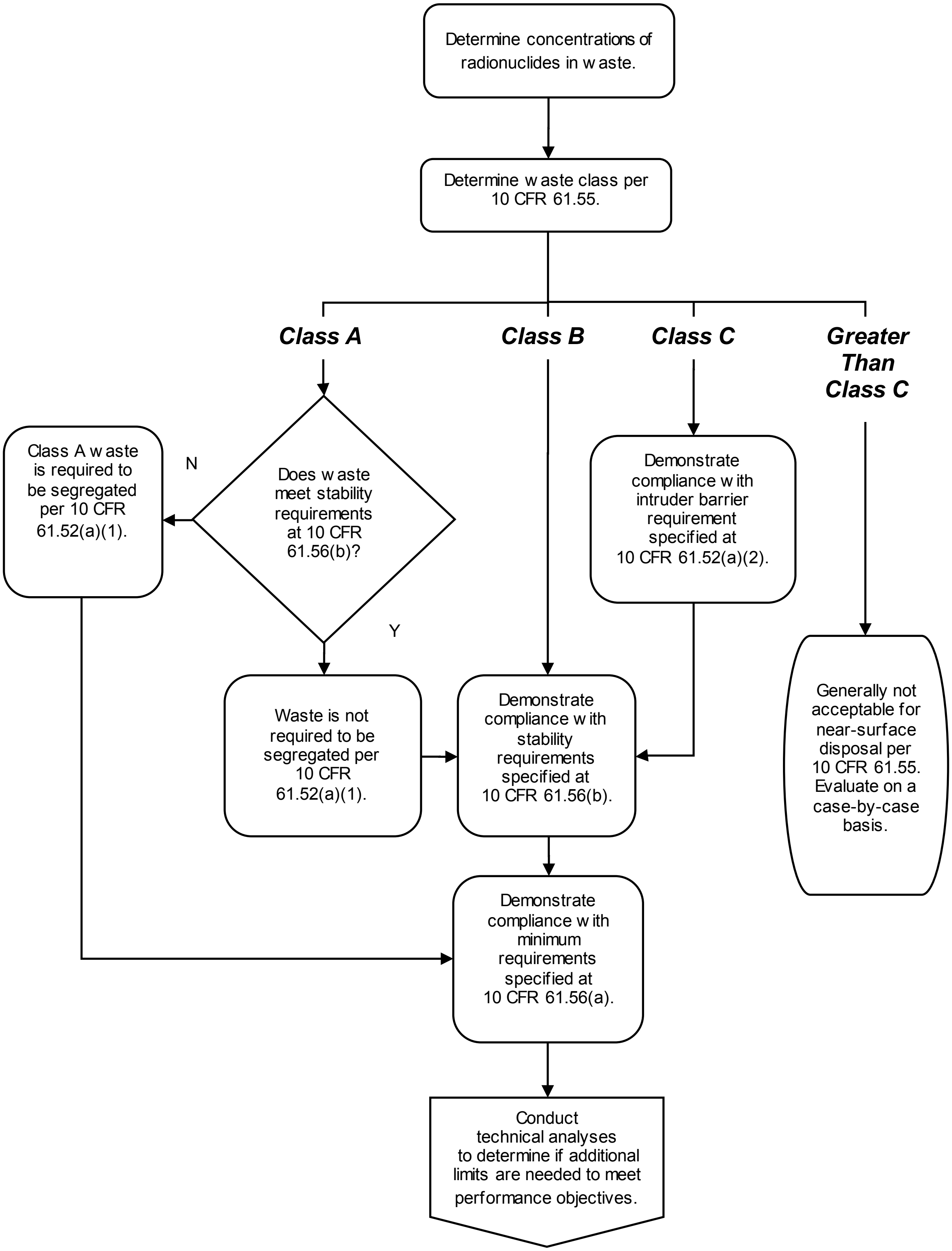

Figure 9-4 Waste Classification and Segregation for Waste Classes

1

The approach, established in NUREG-0782 (NRC, 1981a), first considered protection of the individual inadvertent intruder. The approach then identified a limited set of radionuclides that are significant from the standpoint of migration. Radionuclides significant from the standpoint of migration are generally more important for protection of the general population; therefore, the NRC staff expected these radionuclides to be evaluated as part of the demonstration that the performance objective for protection of the general population (i.e., 10 CFR 61.41) is met. Therefore, the waste classification requirements were primarily derived from the analysis for protection of the inadvertent intruder.

For near-surface disposal, 10 CFR 61.55 specifies the three classes of waste, A, B, and C, that resulted from the analysis. Upper concentration limits are also defined for Class C waste. Wastes containing radionuclide concentrations higher than the upper limits would be generally unacceptable for near-surface disposal. However, there may be instances where these wastes would be acceptable for near-surface disposal with special processing or design. These instances would be evaluated on a case-by-case basis.

Wastes for which there are no stability requirements, but which must be disposed of in a segregated manner from other wastes, are termed “Class A.” These wastes are defined in terms of maximum allowable concentrations of certain isotopes and certain minimum requirements on wasteform that are necessary for safe handling. The minimum requirements are specified in 10 CFR 61.56(a). Waste designated as Class A must be segregated from other waste as required in 10 CFR 61.52(a)(1), unless a licensee can demonstrate that the waste also meets the stability requirements specified in 10 CFR 61.56(b). The technical analyses required in 10 CFR 61.13 could demonstrate based on site-specific conditions that additional disposal practices or waste characteristics—such as those required for Class B or C wastes—would be necessary to demonstrate that the performance objectives are met.

Wastes that need to be placed in a stable form and disposed of in a segregated manner from unstable wasteforms are termed “Class B.” These stable wastes are also defined in terms of allowable concentrations of isotopes and requirements for a stable wasteform as well as minimum handling requirements. The minimum requirements are specified at 10 CFR 61.56(a), and the stability requirements are specified at 10 CFR 61.56(b). Further, the technical analyses could demonstrate that additional disposal practices or waste characteristics, such as those required for Class C waste, would be necessary, based on site-specific conditions, to demonstrate that the performance objectives are met.

Wastes that need to be placed into a stable form, disposed of in a segregated manner from unstable wasteforms, and disposed of so that a barrier is provided against potential inadvertent intrusion after institutional controls are no longer assumed to be effective are termed “Class C.” These intruder wastes are also defined in terms of allowable concentrations of isotopes and requirements for disposal by deeper burial or some other intruder barrier, as well as minimum stability requirements. The minimum requirements for waste characteristics are specified at 10 CFR 61.56(a), and the stability requirements are specified at 10 CFR 61.56(b). Requirements for near-surface disposal by deeper burial or some other barrier are specified at 10 CFR 61.52(a)(2). The technical analyses could demonstrate that additional disposal requirements, such as the longevity of the intruder barriers, or limits on the radionuclide inventory, are necessary to provide reasonable assurance that the performance objectives would be met.

Because the classification limits were developed primarily from an analysis that examined inadvertent intrusion, the limits are not intended to provide reasonable assurance that all the performance objectives of 10 CFR Part 61 will be met. Therefore, licensees using the waste classification requirements may need to develop additional limits based on the results of the technical analyses used to demonstrate that the remaining performance objectives would be met. For example, radionuclides that are prone to migration may require additional limits to ensure that the 10 CFR 61.41 performance objective will be met.

As specified in 10 CFR 61.55(a)(6), waste that does not contain any radionuclides listed in either Table 1 or 2 is considered Class A. As such, this waste is subject to the same requirements as Class A waste that does contain radionuclides listed in either Table 1 or 2. However, the technical analyses could demonstrate that additional disposal practices, such as those required for Class B or C wastes, are necessary to provide reasonable assurance that public health and safety will be protected. Therefore, licensees may also need to specify limits for those radionuclides that are not specifically identified in the waste classification requirements in 10 CFR 61.55 if the radionuclides significantly affect the demonstration that the performance objectives would be met. In these cases, licensees should refer to Section 9.1.1.1 for guidance on developing allowable limits from technical analyses.

NRC has developed guidance on classifying waste according to the waste classification requirements. The guidance includes a BTP, “Final Waste Classification and Waste Form Technical Position Papers,” dated May 11, 1983, which presents guidance on classifying waste (NRC, 1983d). The NRC staff has also developed guidance on acceptable methods of concentration averaging in a BTP on concentration averaging and encapsulation (NRC, 1995b) and recently published a revised draft for comment (NRC, 2012a). Guidance is also available in Standard Review Plan 4.1 of NUREG-1200 (NRC, 1994) to assist reviewers in determining whether licensees have adequate procedures to ensure that waste disposal is conducted in compliance with 10 CFR 61.55 and 10 CFR 61.56.

9.1.1.3 *Insignificant Radionuclides*

Licensees may choose not to develop limits for radionuclides that contribute, in aggregate, a projected dose of no greater than 10 percent of the limits prescribed in the performance objectives. That is, the sum of the contributions from all radionuclides considered insignificant should be no more than 10 percent of the limit for a particular performance objective. However, radionuclides that could be excluded based on comparison to the limit for one performance objective (e.g., protection of the public from releases) may need to have limits to comply with another performance objective (e.g., protection of inadvertent intruders). Once a licensee has demonstrated that radionuclides are insignificant, the dose from the insignificant radionuclides must be accounted for in demonstrating that the performance objective is met, but insignificant radionuclides may be excluded from further detailed evaluation in the technical analyses.

When radionuclides are considered insignificant and eliminated from further consideration, licensees should justify the decision to consider them insignificant. However, licensees should be aware that these decisions may need to be revisited if warranted by new information. For instance, if a disposal facility proposes to accept new waste streams with significantly different radionuclide inventories than previously considered, the licensee may need to assess whether radionuclides that were previously considered insignificant continue to remain so. Further, if a licensee obtains updated information suggesting that its understanding of the behavior of a radionuclide in the site environment has significantly changed, they should reassess the significance of the radionuclide to meeting the performance objectives.

9.1.1.4 *Application of Allowable Limits*

In general, licensees will need to develop the allowable limits on a radionuclide-by-radionuclide basis. Because the performance objectives are based on the total contribution of all radionuclides to the dose limits, licensees will need to perform a sum-of-fractions calculation to demonstrate the allowable limits are met. Sum-of-fractions calculations are also performed for waste classification under 10 CFR 61.55(a)(7). In general form, licensees can use the following relationship to sum the ratio of the activity to its corresponding allowable limit for each radionuclide present in the waste:

$$\sum_{i=1}^{N} \frac{Activity_i}{Limit_i} \leq 1 \qquad (9.2)$$

where

$Activity_i$ is the total activity [Bq] or activity concentration [Bq/m^3 (Ci/m^3) or Bq/g (Ci/g)] of radionuclide *i*; and

$Limit_i$ is the allowable limit [Bq (Ci), Bq/m^3 (Ci/m^3) or Bq/g (Ci/g)] of radionuclide *i* from the most restrictive scenario used to demonstrate the performance objectives would be met.

Licensees should also develop a mechanism to report the inventory that has been disposed of and identify when action may be needed. Types of actions that could be taken may include the following:

- Notify the regulator that a certain percentage of the allowable limit has been received.
- Evaluate whether any updates to the technical analyses are needed.
- Update the technical analyses (establish new allowable limits).
- Modify the disposal facility design, including acceptable wasteforms (see Section 9.1.2).
- Limit or prohibit further disposal of a certain type of waste (see Section 9.1.3).

When significant changes to the operations of the disposal facility occur, licensees should consider updating the allowable limits. Some operational changes may simply require that a licensee performs an assessment of the impact on the allowable limits; however, no change to the allowable limits is required. Other operational changes may require the licensee to re-examine the allowable limits. These changes may include, but are not limited to, a proposal to receive new material, receipt of significant new information on the site characteristics or engineering design, changes to intruder barriers, changes to the understanding of the performance of key components of the disposal system, and updating of the technical analyses. It is important for licensees to establish early in the process the criteria for updating and revision. If a licensee uses a process to determine the significance of a potential change to the established allowable limits, they should maintain a comprehensive list of all items that were screened from impacting the allowable limits. The cumulative impact from many small changes can be additive such that, in total, the allowable limits would require revision to avoid future mitigation.

If a licensee revises allowable limits, they should provide regulators a clear basis for the revisions that includes a side-by-side comparison of changes to parameters or models and the basis for those changes. The side-by-side comparison will provide transparency for the revisions and will facilitate the regulator's review of the revised allowable limits. It may also have the complementary benefit of enhancing stakeholder confidence in the revisions. If limits are relied upon to demonstrate defense-in-depth protections, the licensee should provide a basis that defense-in-depth protections remain adequate in light of the proposed change.

9.1.2 Acceptable Wasteform Characteristics and Container Specifications

Section 61.58(a)(2) of 10 CFR Part 61 requires licensees to specify acceptable wasteform characteristics and container specifications as part of the waste acceptance criteria. Acceptable wasteform characteristics and container specifications, together with the other waste acceptance criteria (e.g., radionuclide limits), provide reasonable assurance that the performance objectives will be met and may provide defense-in-depth protections. Acceptable wasteform characteristics and container specifications include properties that facilitate handling of the waste at the disposal facility, promote stability of the waste to minimize subsidence and water contact with the waste, minimize release and migration of the radionuclides from the disposal site, deter or preclude inadvertent intrusion into the waste, or limit exposures during operations.

The regulations require that all waste meet the minimum requirements specified in 10 CFR 61.56(a). The minimum requirements are designed to facilitate handling of waste and protect the health and safety of personnel at the disposal facility. Licensees may also identify additional minimum criteria to facilitate handling and protect facility personnel depending on the particular operational practices and environmental conditions at a disposal facility. Additional minimum criteria might include acceptable limits for waste package external surface dose rate and heat generation, necessary labeling and marking to be applied to waste packages, container specifications, or specific requirements for acceptance of bulk waste. Licensees should provide a rationale for inclusion of the additional minimum criteria which should include a demonstration that they are comprehensive. The basis, as appropriate, should identify why the additional criteria were developed and include the performance objective(s) that the additional criteria support and whether the criteria are considered defense-in-depth protections.

Certain waste streams will need to meet more rigorous requirements on wasteform than the minimum requirements to ensure stability after disposal and demonstrate compliance with the performance objectives. The requirements to ensure stability are specified in 10 CFR 61.56(b). For licensees relying on the waste classification requirements to develop waste acceptance criteria, Class B and Class C waste must meet the requirements to ensure stability. Licensees developing waste acceptance criteria from the results of the technical analyses will need to identify the wastes that will need to meet stability requirements.

Licensees may demonstrate that the stability requirements would be met by using one or more of the following approaches - a stable wasteform, a container that provides stability, or facility design. The approach, or combination of approaches, that a licensee uses to demonstrate stability will determine the waste acceptance criteria needed to ensure stability and defense-in-depth protections. For example, if a licensee constructs a reinforced concrete vault and demonstrates that it provides adequate stability for the required timeframe, the waste acceptance criteria may not need to address stable wasteforms or container specification for stability. In general, stable wasteforms or container specifications for stability are necessary when degradation of the waste may significantly affect meeting the performance objectives. For example, stable wasteforms or containers would be necessary for wasteforms with sufficient radioactivity such that its release from the disposal site would significantly affect public health and safety. Likewise, stable wasteforms may be necessary for higher activity waste to minimize exposures to inadvertent intruders since stable wasteforms tend to provide a recognizable and non-dispersible waste.

Licensees should provide a technical basis for the criteria for allowable wasteform characteristics and container specifications. Licensees relying on the waste classification requirements to develop waste acceptance criteria may use the requirements of 10 CFR 61.56 as a basis. Licensees developing waste acceptance criteria from the results of the technical analyses should clearly identify how the acceptable wasteform characteristics and container specifications are consistent with the assumptions, modeling approaches, and results of the technical analyses. The basis, as appropriate, should also identify which performance objective(s) the criteria support and whether the criteria provide defense-in-depth protections. Further, the basis should identify the time period over which the criteria are intended to protect public health and safety. For example, some acceptable wasteform characteristics may only need to be relied upon to protect facility personnel during operations; other acceptable wasteform characteristics may be important to protect the general population from releases of radioactivity from longer-lived waste or intruders from inadvertent exposures to longer-lived waste farther into the future. The criteria should provide reasonable assurance that the longevity required of the wasteform and container capabilities is and can be adequately demonstrated. In some cases this may involve criteria to document traditional engineering tests or specifications for waste containers. In other cases, the criteria may be more rigorous and include laboratory testing, predictive modeling, or comparison to analogs. In still other instances, the duration of time that stability of the wasteform or containers is required may be so long that the uncertainty in material behavior may preclude a reasonable demonstration of stability. In these instances, licensees should not solely rely upon wasteform characteristics or container specifications to ensure safety. Rather, other limits or defense-in-depth protections may need to be imposed such as allowable limits.

NRC has developed guidance in the form of a BTP (NRC, 1991b) for waste generators on wasteform test methods and results that are considered acceptable for complying with the 10 CFR Part 61 stability requirements. The guidance also identifies conditions that stable wasteforms should meet to demonstrate that the stability requirements are met. The guidance is applicable for licensees who develop waste acceptance criteria from the 10 CFR Part 61 waste classification requirements. The guidance is also considered generally applicable to licensees who develop waste acceptance criteria from the results of the technical analyses required in 10 CFR 61.13. However, there may be specific cases where the approaches need to be amended due to site-specific conditions. In these cases, licensees should provide a technical basis for the divergence from the BTP on wasteform test methods (NRC, 1991b). Licensees may also consult IAEA-TECDOC-864 (IAEA, 1996), which provides considerations for establishing container specifications. Section 3.2.4 of this document provides guidance associated with wasteforms.

Reviewers should coordinate reviews of the acceptable wasteform characteristics and container specifications with the reviews of the technical analyses required to meet 10 CFR 61.13 (see Sections 3.2.4, 4.3, and 8.0). Reviewers should verify that the licensee's proposed criteria for wasteform characteristics and container specifications are reasonably consistent with the wasteforms and containers assessed in source terms for the performance assessment and intruder assessment, as well as assessments of expected and accidental occupational exposures during handling storage, and disposal of waste. In other words, licensees should establish criteria for wasteforms and containers that ensure the wasteforms and containers will provide the expected performance relied upon in the technical analyses including defense-in-depth capabilities.

In general, reviewers should focus their review of wasteform characteristics and container specifications on waste streams that are expected to contribute most significantly to risk to the public, workers, and the environment. The significant wasteform characteristics and container specifications are likely to vary depending upon the disposal site characteristics and engineering design. Reviewers should evaluate the licensee's technical analyses to understand which wasteform characteristics and container specifications are important for demonstrating that the performance objectives are met. These may include mechanical properties to ensure stability or limit the likelihood or consequences of potential accidents during operations. They may also include durability or leaching characteristics to minimize releases to the general environment. Further, reviewers should evaluate whether the allowable wasteform characteristics and container specifications would significantly affect the stability of the disposal site after closure. For example, reviewers may need to evaluate whether waste containers could withstand anticipated mechanical loads after disposal. Reviewers should coordinate their review of the development of acceptable wasteform characteristics and container specifications with their review of allowable limits from the technical analyses (see Section 9.1.1.1).

Reviewers should also evaluate whether the technical basis provided for each criteria will provide assurance that all the performance objectives will be met. For example, if a particular wasteform characteristic or container specification is based on the results of the performance assessment, reviewers should confirm that the limit would not preclude licensees from demonstrating that the other performance objectives (e.g., protection of inadvertent intruders via the intruder assessment) are also met. Reviewers should also evaluate whether the criteria ensure that the wasteform characteristics and container specifications are expected to persist for the duration needed to demonstrate compliance with the performance objectives. Reviewers may elect to conduct independent analyses to inform the review.

9.1.3 Restrictions or Prohibitions

Section 61.58(a)(3) of 10 CFR Part 61 requires licensees to specify restrictions or prohibitions on waste, materials, or containers that might affect meeting the performance objectives. Licensees should identify any specific radionuclides, chemical or hazardous materials, or specific containers or types of containers that are restricted or prohibited from acceptance at the facility. The restrictions and prohibitions should adequately reflect those identified in the minimum waste characteristic requirements specified in 10 CFR 61.56(a).

Reviewers should assess the licensee's list of restrictions or prohibitions to ensure it is comprehensive and adequately considers the minimum waste characteristics requirements specified in 10 CFR 61.56(a). Reviewers should also assess whether the licensee's list is consistent with the assumptions, modeling approaches, and results of the technical analyses used to demonstrate that the performance objectives would be met. Reviewers may perform independent modeling to assist this review.

9.2 Waste Characterization Methods

Licensees are required, per 10 CFR 61.58(b), to provide methods for characterizing waste for acceptance. The methods shall identify the parameters to be characterized and the level of uncertainty in the characterization data that is considered acceptable. The regulations specify that, at a minimum, the following information must be required to adequately characterize waste for acceptance:

- **Physical and chemical characteristics**. Information on the physical and chemical characteristics of the waste support handling, the determination of compatibility with the container and other waste, as well as any potential treatment or conditioning processes. Physical characteristics may include a description of the material including its density, consistency, and appearance. Chemical characteristics may include pH, reactivity, chemical compounds present, and the presence of hazardous or toxic constituents.

  Volume, including the waste and any stabilization or absorbent media. Information on volume supports waste handling decisions. The information is also important to determine or verify the concentration of radionuclides for comparison with the waste acceptance criteria. Volume information should include container volume, actual waste volume, and the container utilization factor. The container utilization factor represents the portion of the container value that is filled with waste, including stabilization or absorbent media. Information on the container volume should represent the volume of the disposal site that will be occupied by the container. Information on the actual waste volume should include stabilization or absorbent media. If used, stabilization or absorbent media should be identified.

- **Weight of the container and contents.** Information on weight should include container weight (or mass) that would have to be handled. Weight information may be important for meeting stability criteria as well as transportation requirements. This information is also important to determine or verify the concentration of radionuclides for comparison to the waste acceptance criteria.

- **Identities, activities, and concentrations of radionuclides.** This information may include the total activity in a container, the identities and activities of the significant radionuclides per unit volume or mass, radiation dose levels at the surface of the container, and external contamination levels on the surface of the container. Significant radionuclides are primarily those that affect the demonstration that the performance objectives would be met. Significant radionuclides also include radionuclides important for waste classification.

- **Characterization date.** The characterization date helps determine the validity of the characterization documentation.

- **Generating source.** Identification of the generating source helps determine the validity of the characterization documentation. Information on the generating source may include packaging date, generator site, location of the process which generated the waste, and information on conditioning, if applicable.

- **Any other information needed to characterize the waste to demonstrate that the waste acceptance criteria are met.** This information includes any additional data about the waste that are important to the facility's ability to protect public health and safety. This information should be identified from waste acceptance criteria which are drawn from either the results of the technical analyses that are used to demonstrate that the performance objectives or the waste classification requirements are met. For example, data on mechanical properties of wasteforms or containers may be needed to ensure that any criteria for stability, as necessary, can be met.

The purpose of these requirements is to ensure that knowledge of the waste's characteristics is (1) commensurate with the assumptions and approaches employed in the technical analyses used to develop the proposed waste acceptance criteria and is, thus, (2) sufficient to demonstrate that the waste acceptance criteria are met.

For waste acceptance criteria developed from the waste classification requirements specified in 10 CFR 61.55, waste characterization methods should be commensurate with the assumptions and approaches employed to develop the waste classification requirements. For waste acceptance criteria developed from the technical analyses, waste characterization methods should be consistent with the approaches employed in the analyses. In other words, for each of these two approaches to develop waste acceptance criteria, there will have been assumptions and approaches employed to derive the criteria. The methods should ensure that significant assumptions or approaches are characterized sufficiently to provide assurance that the criteria can be met. For example, the limits for Class B and C waste, per the 10 CFR 61.55 waste classification requirements, were developed from an analysis that assumed Class B and C waste would be stable. As a result, 10 CFR Part 61 includes requirements that Class B and C waste must be disposed in a stable form. Therefore, licensees may need to specify waste acceptance criteria to ensure that Class B and C waste are stable. In this example, licensees would also need to specify acceptable methods to characterize the waste to demonstrate that the stability criteria will be met.

Regardless of the method used to develop waste acceptance criteria, licensees should specify acceptable methods to characterize waste, criteria for determining an acceptable level of uncertainty in the characterization data, and documentation required to ensure sufficient detail is available to demonstrate that the waste acceptance criteria of the land disposal facility are met.

9.2.1 Acceptable Waste Characterization Methods

Licensees shall specify methods for adequately characterizing waste for the purposes of demonstrating that the disposal facility's waste acceptance criteria are met. These specifications should identify methods for characterizing the radionuclide content of the waste, as well as any significant waste characteristics and container specifications. The intent of the methods should be to ensure that generators provide reasonably realistic representations of the radionuclide content of their waste and the necessary waste characteristics for comparison with the waste acceptance criteria. In general, the characterization methods would be specific to each individual waste stream, and would consider the different radiological and other characteristics of the waste streams destined for disposal at a land disposal facility. Ideally, the disposal facility operator should ensure that the generator's characterization is near in time to the demonstration that waste meets the acceptance criteria. When proximate characterization is not possible and the time interval from characterization to disposal may significantly affect meeting the waste acceptance criteria, the disposal facility operator should ensure that a basis supports why earlier characterization remains acceptable for demonstrating that the waste acceptance criteria are met. IAEA has developed guidance on strategies and methodologies for radioactive waste characterization that licensees may find applicable to develop acceptable waste characterization methods (IAEA, 2007).

9.2.1.1 *Acceptable Methods for Characterizing Activities and Concentrations*

The first step in characterizing the waste to meet the waste acceptance criteria is to determine the activities and concentrations of significant radionuclides in the waste. Licensees may use a variety of methods to determine radionuclide activities or concentrations in LLW. Acceptable methods would likely include either direct measurement of individual radionuclides or indirect methods that infer activities or concentrations of radionuclides from other measurements or knowledge of the waste to enhance confidence that the waste acceptance criteria are met. These methods are described in more detail in the BTP on radioactive waste classification and wasteforms (NRC, 1983d).

Direct measurement of individual radionuclides generally provides the most confidence that the allowable activities and concentration limits identified in the waste acceptance criteria are met. However, the NRC staff recognizes that direct measurement may not always be necessary or warranted. For example, activities or concentrations of certain radionuclides may be overly difficult to measure with current technology (e.g., below minimum detection capabilities) or personnel safety considerations may limit direct measurement of specific waste streams. In these cases, licensees are permitted to accept other methods (e.g., indirect or material accountability methods) to demonstrate that the allowable limits are met.

Indirect methods infer radionuclide activities or concentrations from a number of approaches which include materials accountability, characterization by source, and the use of scaling factors. Radionuclide material accountability relies on inferences from the difference between the quantity of radioactive material entering and exiting a given process. Characterization by source is similar to material accountability and involves determining the radionuclide content through knowledge and control of the source of the waste. Indirect methods often rely on the use of scaling factors to relate the inferred activity or concentration of one radionuclide to another radionuclide or gross radioactivity that is measured.

Indirect methods may be appropriate to determine activities or concentrations of difficult-to-measure radionuclides provided there is reasonable assurance that the indirect methods can be correlated with actual measurements. Licensees should require that generators develop correlations between measured or known quantities and the inferred quantity on a generating facility and waste stream basis. NRC guidance on the use of indirect methods to determine the inventory of radionuclides will be summarized in a Regulatory Issue Summary in 2015. The BTP on radioactive waste classification provides additional guidance on acceptable uses of indirect methods for use in waste classification (NRC, 1983d). This guidance may also be useful for identifying methods to demonstrate that the allowable limits developed from technical analyses are met. Licensees should also consider the issues identified by the NRC staff in *Information Notice 86-20* (NRC, 1986b) when specifying criteria for application of indirect methods to meeting the allowable limits. Further, NUREG/CR-6567 (NRC, 2000b) and IAEA (2009) provide information on scaling factors that licensees may wish to consider when identifying criteria for the use of indirect methods. Although previous NRC guidance is focused on determining concentrations for demonstrating compliance with allowable limits developed from the waste classification requirements of 10 CFR Part 61, they may also be applicable, on a case-by-case basis, for determining limits for demonstrating that allowable limits developed from the technical analyses are met. Land disposal facility operators should require generators to provide information as part of certification that details how scaling factors are derived and whether periodic re-analysis of the scaling factors resulted in a revision to the scaling factors. If a generator determines that scaling factors need to be revised, a determination should be made whether the revision affects previous shipments of waste to the facility. Land disposal facility operators should assess any impacts to acceptable inventories, both previous disposals and future acceptable waste acceptance criteria that may result from revisions to scaling factors.

Each of these methods is subject to various sources of uncertainty (Figure 9-5), including, but not limited to, the following:

- a sample's degree of representativeness of the whole, due to temporal and spatial variability in:
  - concentrations of directly sampled radionuclides
  - samples used to establish scaling factors
  - samples used to establish concentrations of process inputs
- analytical uncertainty in sampled radionuclides
- uncertainty in dose rate scans
- uncertainty in any scaling factors for unsampled containers
- uncertainty in radionuclide concentrations in inputs and input volumes, if the radionuclide concentrations in the product are based on the inputs and are not independently measured

9.2.1.1.1 Characterization Methods for Criteria Based on the Waste Classification Requirements

The BTP on radioactive waste classification and wasteforms provides guidance on the use of various methods to determine concentrations to demonstrate that allowable concentrations developed from the 10 CFR Part 61 waste classification requirements are met (NRC, 1983d). The BTP indicates that the NRC staff considers a reasonable target for determining measured or inferred radionuclide concentrations to be that concentrations are accurate to within a factor of 10. However, more precision may be required in certain cases to demonstrate that the performance objectives will be met. In general, licensees should reflect uncertainty in radionuclide activities and concentrations in the technical analyses.

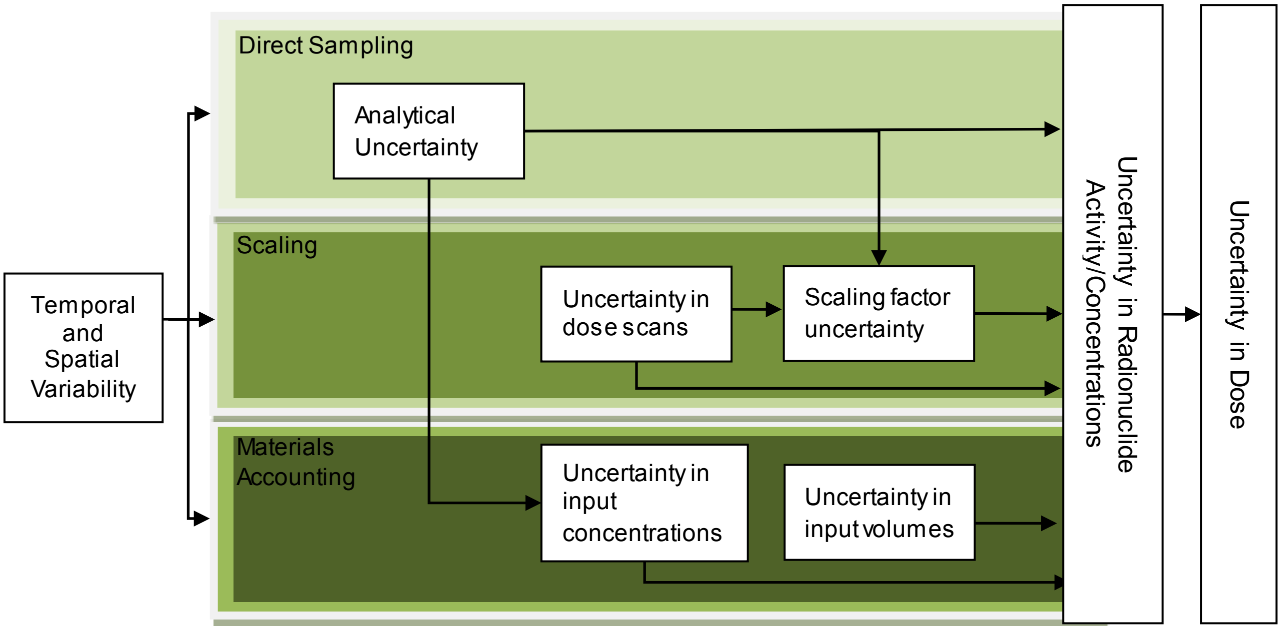

Figure 9-5 Sources of Uncertainty in Various Methods of Determining Radionuclide Activities or Concentrations in Waste Packaged for Disposal

Section 61.55(a)(8) of 10 CFR Part 61 provides acceptable methods for determining radionuclide concentrations for comparison with allowable activities and concentrations that are developed from the waste classification requirements. A licensee may average the concentration of a radionuclide over the volume of the waste, or the weight of the waste, if the concentration units are expressed as nanocuries per gram. The NRC staff has developed guidance on acceptable methods of concentration averaging in a BTP on concentration averaging and encapsulation (BTP CA) (NRC, 1995b) and recently published a revised draft for comment (NRC, 2012a). The revised draft BTP CA is based on many of the same methods for performing an intruder assessment that were used to develop this guidance.

For example, the revised draft BTP CA considers the intruder receptor scenarios described in Section 4.3.1.1 of this document in developing guidance on acceptable averaging approaches (NRC, 2012a). However, the revised draft BTP CA also considers receptor scenarios in which an individual may be exposed to discrete items (NRC, 2012a). For instance, the NRC staff considered a waste-handling receptor scenario to develop the revised draft BTP CA for disposal of discrete sources, which is not discussed in this guidance for intruder assessments (NRC, 2012a). The NRC staff used these receptor scenarios to develop the revised draft BTP CA for limiting the range of waste concentrations that can be mathematically averaged in a single container, as well as specific guidance on appropriate waste volumes over which concentrations should be averaged for waste classification by waste generators or processors (NRC, 2012a). This guidance—as opposed to the guidance in the revised draft BTP CA (NRC, 2012a)—focuses on determining appropriate concentrations to use in site-specific intruder analyses performed by land disposal facility licensees. Irrespective of any concentration averaging used to determine waste classification, radionuclide concentrations should be representative of the actual waste distribution (see Section 4.3.2.2.2 of this guidance), although conservative assumptions are, in general, appropriate.

9.2.1.1.2 Characterization Methods for Criteria Based on the Results of the Technical Analyses

Licensees developing waste acceptance criteria from the results of the technical analyses must identify acceptable methods for characterizing the waste to demonstrate that the waste acceptance criteria are met. The appropriate method for characterizing the waste will depend on the specific parameter being measured, the hazards associated with acquiring the information, and the amount and quality of the data needed to adequately characterize the waste.

The specific parameters and the quantity and quality of the data should be consistent with the intended use of the information, namely to demonstrate that the waste acceptance criteria are met. In this case, the criteria are developed from the results of the technical analyses. Therefore, the parameters and the data developed to characterize the parameters should be consistent with the analyses. In other words, characterization parameters should focus on those parameters of the analyses which are significant for a licensee's demonstration that the performance objectives are met and that defense-in-depth protections are provided. Licensees should identify significant parameters of the analyses as criteria for waste acceptance. Likewise, the quantity and quality of data should be commensurate with the parameter's importance to meeting the performance objectives. Licensees may use a graded approach in defining the level of quality for the data. Therefore, characterization data for parameters that are more significant for demonstrating that the performance objectives would be met should generally require more robust pedigree than data for parameters of lesser significance. Likewise, characterization data for parameters that are considered defense-in-depth protections should generally require more robust pedigree than data for parameters that are not relied upon for defense-in-depth.

As discussed in Section 9.2.1.1, adequate waste characterization may include a combination of both direct and indirect methods. Direct methods may include sampling and laboratory analysis as well as certain non-destructive evaluation techniques. Indirect methods may use non-destructive evaluation techniques as well as acceptable knowledge to supplement or provide data that might otherwise be collected by direct methods. The BTP on radioactive waste classification provides guidance on the use of various methods to determine concentrations to demonstrate that allowable concentrations developed from the 10 CFR Part 61 waste classification requirements are met (NRC, 1983d). The revised draft BTP CA is also available to licensees (NRC, 2012a). The methods discussed in these documents may also be appropriate for use in characterizing waste for meeting waste acceptance criteria developed from the results of the technical analyses. Licensees should provide a basis for inclusion or exclusion of the methods discussed in the BTP on radioactive waste classification and wasteform (NRC, 1983d) for characterizing data to meet waste acceptance criteria developed from the results of the technical analyses. The basis should include either a description of why the method from the BTP on radioactive waste classification and wasteform (NRC, 1983d) is appropriate or inappropriate depending upon whether it is included or excluded.

9.2.1.2 *Acceptable Methods for Characterizing Wasteform and Containers*

Section 61.56 of 10 CFR Part 61 specifies requirements for waste characteristics, which apply to all waste classes, as well as stability requirements, which are required only for Class B and C wastes because of their higher radioactivity. Waste stability helps to limit inadvertent intrusion exposures and minimize water infiltration into the disposal units. Wastes that are stable, and thus recognizable after the active institutional control period has ended, ensure that the impacts of inadvertent intrusion remain limited to discovery-type receptor scenarios. To the extent practical, Class B and C wastes should maintain their gross physical properties and identity over a 300-year period to be consistent with the concepts in 10 CFR 61.7(b)(2). However, certain waste may need to meet the stability requirements for longer periods of time in order for a licensee to demonstrate that the performance objectives would be met.

The NRC staff has developed guidance on wasteforms to comply with waste characteristic requirements in its BTP on wasteforms (NRC, 1991b). The guidance also applies to Class A waste that is not segregated from Class B and C wastes. Additional requirements, specified as license conditions, may be necessary for waste, including that categorized as Class A by 10 CFR 61.55(a)(6). Regulators can specify additional requirements in license conditions based on the need to mitigate potential exposures as demonstrated in the technical analyses.

Licensees should specify methods for characterizing the wasteform and container. Characterizing the waste to demonstrate that acceptable wasteform characteristics and container specifications are met is generally a two-staged process. First, the licensee should require generators to define the wasteform characteristics and container attributes, which includes performance data (e.g., compressive strength, load bearing capability, resistance to impact, corrosion, fire resistance, etc.). The disposal facility operator should identify which quality-related parameters need to be controlled, including any necessary details of the arrangements for controlling them, in order to provide confidence that the acceptance criteria are met. Second, the licensee should require that generators confirm that the wasteform or container conforms to the applicable specifications. The disposal facility operator should ensure that the generator's confirmation of the applicable specifications meets the quality requirements for the characterization. In some instances, this may include the timeliness of the generator's confirmation. For instance, if a waste container's structural stability is important (e.g., a defense-in-depth protection) and the waste is planned to be stored for extended periods prior to shipment for disposal, the environment in which it is stored may need to be controlled to ensure that an earlier characterization of the container's stability is adequate to meet the acceptance criteria at the time of disposal.

9.2.2 Data Quality Objectives Process

Demonstrating that the waste acceptance criteria are met is a process that is supported by waste characterization data. For most waste, this decision is supported by statistical tests based on the results of one or more direct samples. The initial assumption, or null hypothesis, that a licensee should use is that each parameter to be characterized exceeds the allowable limits specified in the waste acceptance criteria. The characterization should be designed to provide information to reject this initial assumption. The NRC staff recommends that licensees use the Data Life Cycle as a framework for planning, implementing, and evaluating characterization results prior to making a decision. Licensees and generators should coordinate to apply the framework or a similar methodology to the waste characterization activities. Figure 9-6 summarizes the major activities associated with each phase of the Data Life Cycle for waste characterization.

One aspect of the planning phase of the Data Life Cycle is the Data Quality Objectives (DQOs) process. The DQO process is a series of seven planning steps for establishing criteria for data quality and developing characterization plans:

1. State the problem;
2. Identify the goals of the study;
3. Identify inputs to the decision;
4. Define the study boundaries;
5. Develop the analytic approach;
6. Specify performance or acceptance criteria; and
7. Develop the plan for obtaining data

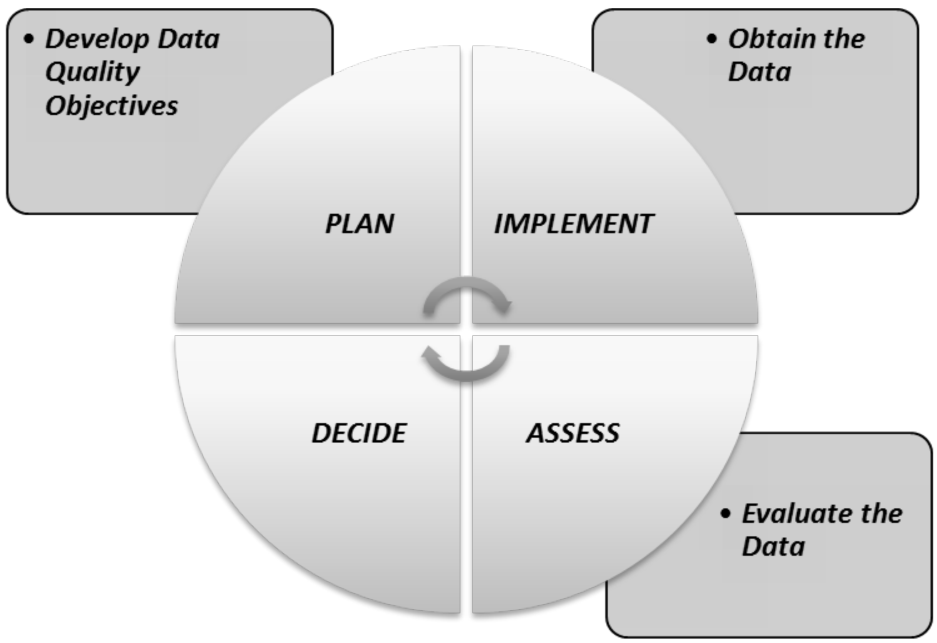

Figure 9-6 Data Life Cycle Framework for Waste Characterization

The process should use a graded approach to data quality requirements. A graded approach is one in which the level of effort required to develop data quality objectives should be commensurate with the importance of the data for demonstrating that the performance objectives would be met. This approach facilitates more effective characterization planning with consideration of how the data will be used. Thus the process should be a flexible planning tool that can be varied from simple to complex depending on the specific situation.

DQOs should be qualitative or quantitative statements that satisfy all of the following:

- Clarify the characterization objective;
- Define the most appropriate type of data to collect;
- Determine the most appropriate conditions for collecting the data; and
- Specify limits on decision errors that will be used as the basis for establishing the quantity and quality of data needed to demonstrate the waste acceptance criteria are met.

Using the DQO process can help ensure that the type, quantity, and quality of data will be appropriate to determine that the waste acceptance criteria are met. Additional guidance on the Data Life Cycle and Data Quality Objectives process is provided in an EPA guidance report (EPA, 2006). The *Multi-Agency Radiation Survey and Assessment of Materials and Equipment* (NRC, 2009) provides guidance for applying the Data Life Cycle to disposition surveys of materials and equipment to ensure the surveys are adequate to meet the disposition requirements. Likewise, the *Multi-Agency Radiation Laboratory Analytical Protocols Manual* (NRC, 2004b) provides guidance for the application of the Data Life Cycle to projects that require the laboratory analysis of radionuclides to ensure that the laboratory data will meet the data requirements. These guidance documents may be useful to licensees to develop data quality objectives for generator characterization data that demonstrates the waste acceptance criteria are met.

9.2.3 Documentation

Licensees should require waste generators to provide sufficient waste characterization documentation to ensure that the waste is adequately characterized to demonstrate that the acceptance criteria are met. The level of documentation that licensees require may vary across the waste streams accepted for disposal depending on both the complexity of the waste streams and the importance of the waste streams to demonstrating that the performance objectives are met or that defense-in-depth protections are provided. The elements of the documentation should typically include the following:

- **Organization and Responsibilities**. Organizations and personnel responsible for waste characterization should be identified. Personnel responsible for collecting and managing characterization data should be properly trained to recognize the significance of the data. Qualifications of personnel should be included to provide assurance that the data are properly collected and managed. For instance, acceptable methods for waste characterization may specify the use of a certified laboratory. In this case, the documentation should include the laboratory's accreditation.

- **Quality Assurance**. Waste characterization data should be collected according to an acceptable QA program. The documentation should identify the QA program. Standard Review Plan 9.1 of NUREG-1200 provides guidance on acceptable QA programs (NRC, 1994).

- **Procedures**. Procedures formalize the process for characterizing the waste. The procedures should describe the steps followed to characterize the waste as well as the administrative processes for ensuring the type, quantity, and quality of data is appropriate to adequately characterize the waste. Procedures should include processes for sampling, packaging, transportation, laboratory analysis, and data control, as appropriate. Standard Review Plan 8.6 of NUREG-1200 provides additional guidance on administrative and operating procedures (NRC, 1994).

- **Records**. Waste characterization records should include those that are necessary to meet the disposal facility's waste acceptance criteria as specified by the waste certification program (see Section 9.3). Records that contain characterization procedures, data, and specifications, including the QA program, should be controlled documents that are subject to review, approval, and distribution procedures, as well as a process for making revisions. Existing record control programs may be adequate to provide the necessary controls.

9.3 Waste Certification Program

Licensees, per 10 CFR 61.58(c), must develop a program to certify that waste meets the acceptance criteria prior to receipt at a disposal facility. Certification of waste also provides assurance that a disposal facility operates within the limits established to demonstrate that the 10 CFR Part 61 performance objectives would be met. Once certified to meet a disposal facility's waste acceptance criteria, waste must then be managed to maintain its certification until its emplacement in a disposal unit.

The regulations specify that the certification program must:

- Designate the authority to certify and receive waste for disposal at the disposal facility;
- Provide procedures for certifying that waste meets the waste acceptance criteria;
- Specify documentation required for waste characterization, shipping and certification;
- Identify records, reports, tests, and inspections that are necessary to maintain and provide criteria for auditing; and
- Provide approaches for managing certified waste to maintain its certification status.

9.3.1 Certification Program

Licensees should develop a certification program that defines administrative procedures to provide assurance that waste and its packaging meets the waste acceptance criteria of the disposal facility prior to receipt of the waste at the disposal facility. The program should also provide a traceable and verifiable record of and basis for certification. The certification program should address the following questions:

- Who is responsible for certifying that waste is acceptable for disposal and what are their required qualifications?
- How and when shall waste be certified as acceptable for disposal?
- What documentation is required to provide a traceable and verifiable record for certification and how will certification be audited?
- How shall waste that has been certified be managed to maintain its certification?

The following sections provide guidance on information to adequately address these questions in order to meet the requirements of 10 CFR 61.58.

The principal documents that constitute the certification program should be subject to controls. Therefore, the certification program should identify which documents are to be controlled such as the waste certification program description, certification procedures, and QA program documentation. Document control includes review and approval, distribution to designated recipients, and a controlled process for making revisions to the documents. Existing document control programs at a disposal facility may provide the necessary controls for the documents that are part of the waste certification program.

9.3.1.1 *Organizations and Responsibilities for Certification*

The land disposal facility operator is responsible for developing the requirements of and managing the certification program. Waste certification is typically performed by the waste generator because they are the most knowledgeable about the waste and can most effectively characterize it as it is generated. As waste progresses toward disposal, characterization to meet the acceptance criteria can become more challenging and expensive to perform. However, in some cases, such as an infrequent generator of small quantities of waste, a waste collector, processor, or the land disposal facility operator may be more qualified to perform the certification on behalf of the generator. The organization responsible for certification must certify that waste is acceptable for disposal at the land disposal facility according to the disposal facility's waste certification requirements and obtain authorization from the land disposal facility operator to transfer the waste for disposal.

A certification program must identify the designated individuals or organizations that are responsible for the certification process. These designees include representatives of the land disposal facility who are responsible for managing the certification program, and representatives of organizations responsible for complying with the land disposal facility's certification program to certify that the waste meets the acceptance criteria. These individuals or organizations may include waste generators, waste collectors, waste processors, the land disposal facility operator, or other organizations or individuals qualified to certify that the waste meets the acceptance criteria. The program should require that personnel who are designated to certify waste be identified, qualified, and approved by the disposal facility operator's designated authority.

The certification program should also identify the training requirements needed for the various individuals who are involved in the program. At a minimum, the program should require training of the official who certifies that the waste meets the acceptance criteria of the disposal facility. In addition, individuals should be trained in the procedures that control the part of the certification process with which they are involved.

9.3.1.2 *Certification Procedures*

Licensees should implement the certification program through the use of documented processes and procedures. The certification program should formalize the processes and procedures for certifying waste and for maintaining certification until the waste is emplaced in a disposal unit.

The procedures should describe the administrative process that designated certification officials should follow to ensure that waste is certified prior to receipt at the land disposal facility. The procedures should require a signed statement certifying that the waste meets the disposal facility's waste acceptance criteria and, therefore, is acceptable for disposal. The signature on the certification statement confirms that the waste has been characterized adequately and necessary shipping requirements have been met.

Waste must be certified prior to shipment to the disposal facility. This requirement ensures that the waste certification program is effective in preventing the transfer of waste that does not meet the waste acceptance criteria of the disposal facility. The requirement also prevents potential hazards associated with managing the waste rejected by the disposal facility to which it is transferred. Requiring certification before waste is transferred also reduces the likelihood of having to recall a waste shipment due to a discovery by the certification official, after the waste is in transit, that the waste does not comply with the waste acceptance criteria. Certification that the waste is ready for transfer and meets the waste acceptance criteria and the applicable transportation regulations is a control point in the transfer process. The procedures controlling waste transfer should not allow transfer to occur unless the certification statement has been signed. Once signed, the certification statement becomes part of the record for the transfer of the waste. Once the waste is certified as acceptable for disposal, the land disposal facility can authorize transfer of the waste for receipt and disposal. The certification program should describe the administrative process for attaining authorization from the disposal facility to transfer the waste for disposal once the waste has been certified.

The procedures should require characterization of the waste, as well as inspection of the characterization process to demonstrate that it meets the acceptance criteria. Guidance on acceptable characterization is discussed in Section 9.2. For waste that does not meet the acceptance criteria when inspected, the procedures should specify the administrative process that a waste generator would need to follow to gain acceptance and properly certify that the waste is acceptable for disposal.

The procedures should also document the necessary steps for complying with the applicable transportation requirements for the transfer of certified waste to the land disposal facility, including those specified by the Department of Transportation and in 10 CFR Part 71. These requirements include the requirements for transfer of waste intended for disposal at a licensed land disposal facility that are found in Appendix G to 10 CFR Part 20.

The procedures should clearly describe the process for maintaining the waste certification until the waste has been placed in a disposal unit at the land disposal facility. Guidance on procedures for maintaining certification is provided in Section 9.3.2. As part of certification maintenance, the certification program should also identify adequate procedures for receipt and inspection of waste at the disposal facility to ensure that arriving waste shipments are in compliance with applicable Federal regulations and the waste acceptance criteria. Standard Review Plan 4.1 of NUREG-1200 (NRC, 1994) provides guidance on developing adequate procedures for receipt and inspection of waste arriving at a disposal facility. Standard Review Plan 8.6 of NUREG-1200 (NRC, 1994) also discusses guidance on administrative and operating procedures that may be applicable. The IAEA has also published guidance on inspection and verification of waste packages for near-surface disposal that may be applicable to developing adequate procedures (IAEA, 2000).

Finally, the procedures should clearly describe the process for restricting access to disposal for waste generators that are not meeting the requirements of the certification program. The procedures should identify conditions that would warrant restriction of generator access to disposal including, for example: radiological contamination; wasteform or container integrity deficiencies; improper characterization; improper manifesting; transportation violations; inadequate nuclear safety limits; and improper certification maintenance. These procedures may include suspension of access to disposal capacity or possible heightened oversight by the disposal facility operator and its regulatory authority, and should describe corrective actions necessary to restore access to the disposal facility following suspension.

9.3.1.3 *Certification Documentation*

The key document in a waste certification is the certification statement. The certification statement is the documentation signed by a designated official that certifies that the waste meets the waste acceptance criteria of the disposal facility. The certification statement should also include information required by the certification program, including radiological properties, wasteform characteristics, and container specifications. Licensees should use the waste acceptance criteria to identify key elements to include as part of the waste certification statement. In addition to the certification statement, documentation should also include confirmation that an official from the disposal facility to which the waste is to be transferred has authorized transfer of the waste to the disposal facility.

The documentation supporting the waste certification statement may include or reference the following information. The land disposal facility may use a graded approach to determine which of the following information is necessary for generators to provide prior to granting authorization to transfer waste to the disposal facility. A graded approach would focus on information that is necessary for generators to provide that is significant for demonstrating the waste acceptance criteria have been met and the waste can be certified as acceptable.

- **Waste Stream Profile**. The waste stream profile is a description of the waste stream, generally identifying the source, physical and chemical description, and upper limits on radionuclides.

- **Radionuclide Content**. Radionuclide content includes the concentration and inventory of radionuclides determined from waste characterization. See Section 9.2 for guidance on waste characterization.

- **Radiological Surveys**. Survey results include the determination of the surface contamination of the waste container and the external dose rate if necessary for waste certification.

- **Waste Container Attributes**. Container attributes include information about the physical attributes (e.g., dimensions) of the container as well as any necessary procurement information relevant to certification. Disposal facility operators may require generators to provide container specifications, particularly if they are relied upon by the land disposal facility operator for defense-in-depth. Each container specification should include a description of the specification's purpose, procedures for complying with the requirements of the specification, description of the container and manufacturing specification, and results of tests to assess the integrity of the container.

- **Uniform Low-Level Radioactive Waste Manifest**. The manifest is required by Appendix G to 10 CFR Part 20 for transfers of waste intended for disposal at licensed land disposal facilities (NRC, 1998).

- **Quality Assurance Records**. QA records may include documentation of testing or inspections required for waste certification, particularly for defense-in-depth protections. The records may also include a statement ensuring access for designees of the land disposal facility to perform audits and inspections. This may include assurance of access to the providers of procured items or services that are significant to certify that the waste acceptance criteria are met.

- **Certification Maintenance Procedures**. Certification maintenance procedures include the processes and controls required to maintain waste certification. Guidance on certification maintenance is provided in Section 9.3.2.

The waste certification program should also identify which records need to be maintained and how they are to be maintained. The certification program may detail specific records management requirements, or may simply invoke an existing acceptable records management program such as one that complies with the requirements of 10 CFR 61.80.

9.3.1.4 *Audits of Certifications*

A certification program should also formalize procedures for independent audits of individuals or organizations designated to certify waste as acceptable for disposal by the land disposal facility operator. Standard Review Plan 8.5 of NUREG-1200 (NRC, 1994) provides guidance on plans for conducting reviews and audits of operational activities important to safety that may also be applicable to audits of the certification process. The periodic audits should provide an independent verification of the implementation of the certification program. The audit procedures should describe the principle documents of the waste certification record that will be audited and the frequency of audits.

The principal documents that should be subject to inspection may include the waste certification statement, procurement or purchasing documents (e.g., for approved containers), radiological survey data, and laboratory testing data for characterization required to demonstrate conformance with the waste acceptance criteria. Audits may also include observation of testing and characterization that are significant to demonstrating the waste acceptance criteria are met as well as how the certification process is implemented by the certifying organization. Licensees may use a graded approach to determine the documents subject to audit and the frequency of the audits for a given certifying organization. The certification program should identify the records required to adequately document the audits and the management requirements for the audit records. Licensees should maintain records of the certification audits for inspection by the NRC.

9.3.2 Certification Maintenance

Waste that has been certified as meeting the waste acceptance criteria for a land disposal facility must be controlled so that the certification remains valid until disposal at the facility. Otherwise, the waste will need to be re-certified. The waste certification program should identify the requirements for protecting the certification status of the waste. These requirements may be specific to a waste stream or applicable to all waste streams. The certifying organization should develop procedures for maintaining the waste certification that comply with the certification program’s requirements. Certification maintenance may be especially important for waste that will be stored for long periods of time or significantly treated or conditioned prior to disposal.

Requirements for maintaining the certification status include protecting the waste container, preventing unauthorized introduction of material into the waste, protecting the data marked on the waste container, and protecting any other capabilities relied upon for defense-in-depth.

Requirements for protection of the waste container may include sufficient protection from the environmental conditions during storage, conditioning, or transport (e.g., precipitation, heat, ultra violet) or designated limits for damage, should it occur. Waste may also need to be controlled in a manner that prevents modifying the contents. These controls may include requirements for tamper indication devices and secured storage depending on the waste stream. It is also important to be able to relate each container to information about the certification of the container. Therefore, licensees may need to have requirements regarding container markings to protect from defacement or removal. Also, licensees should safely store records regarding certification.

9.4 Periodic Review

The regulations at 10 CFR 61.58(f) require disposal facility licensees to review the content and implementation of their waste acceptance program at least annually. The purpose of this review is to ensure that the content of the waste acceptance program continues to be adequate and that the program is being implemented in a way that continues to protect public health and safety. As part of this annual review of the waste acceptance program, disposal facility licensees should also evaluate and document whether waste acceptance criteria continue to be protective of public health and safety. If the evaluation indicates that the waste acceptance criteria continue to provide reasonable assurance that the performance objectives will be met and adequate defense-in-depth will be maintained, the documentation should include the basis for relying on the existing waste acceptance criteria. If the evaluation finds that the waste acceptance criteria no longer provide reasonable assurance that the performance objectives will be met or that defense-in-depth protections are inadequate, the criteria should be updated. The licensee should submit the amended criteria and supporting technical analyses that demonstrate the performance objectives will be met as part of a request for amendment to the license.

Periodic reviews should incorporate the following features to assess procedural compliance, technical performance, implementation, and effectiveness of the facility waste acceptance program:

- **Waste acceptance supervisory reviews**. Onsite waste acceptance supervisors should periodically perform and document reviews of the effectiveness of the waste acceptance personnel in such areas as development of waste acceptance criteria, characterization adequacy, and procedural compliance.

- **Quality assurance audits**. Quality assurance audits should be performed by the onsite auditing group. Personnel in the auditing group should have sufficient waste acceptance training or experience so they can determine whether waste acceptance functions (e.g., characterization or certification) are being performed as required. These audits should also be performed periodically at generators.

- **Corporate or contract audits**. Offsite (corporate or contract) audits and evaluations should be performed to determine whether the waste acceptance program complies with the regulations and other requirements and whether objectives are being met as well as to identify needed program improvements.

Periodic review records should contain the following information to be acceptable: date of the review, name of person(s) who conducted the review, persons contacted by the reviewer(s), areas reviewed, review findings, corrective actions, and follow-up. The licensee is not required to submit documentation of its periodic review to the NRC. Rather, licensees should maintain the records as required in 10 CFR 61.80. However, if a licensee identifies during its periodic review a significant implication for public health and safety or common defense and security, the licensee shall notify the NRC as required by 10 CFR 61.9a(b).

9.5 Mitigation

In some cases, a land disposal facility may learn of new information that indicates that previously disposed of waste may present an unreasonable risk to public health and safety or the environment. For example, the new information may indicate a significant reduction in the expected performance of engineered or intruder barriers or the site characteristics to limit radionuclide release and migration. In these cases, licensees may need to consider mitigation to reduce the impact to humans or the environment to ensure that waste disposal continues to meet the performance objectives with reasonable assurance and provides defense-in-depth protections. Mitigation could take many different forms, such as but not limited to, modification of the disposal facility design or remediation of the disposed waste. This section of the guidance document describes when licensees should consider mitigation, what information they should provide to the regulator to demonstrate that mitigation has been implemented, and what a reviewer should evaluate to verify that mitigation has occurred.

As licensees periodically update the waste acceptance criteria, new information may be learned that, when considered in the technical analyses, could indicate that waste previously accepted for disposal may present an unreasonable risk to public health and safety or the environment. Additionally, prior to final closure of the disposal site, the licensee, per the requirements of 10 CFR 61.28, shall submit an application to amend the license for closure upon which the Commission shall make a determination if there is reasonable assurance that the performance objectives of 10 CFR Part 61 will be met and that defense-in-depth protections have been provided. A component of the application for closure should include a final set of technical analyses and a final revision of the safety case to demonstrate that the performance objectives will continue to be met after closure. If a land disposal facility determines during updates to the waste acceptance criteria or the closure process that the facility is no longer meeting the performance objectives, mitigation is one method of bringing the facility into compliance.

Before engaging in mitigation, a licensee should provide information describing the actions they propose to take, including the basis for those actions. The proposed actions could include modification of the disposal facility design or remediation. Design modifications could include installation of a higher performance engineered cover or the use of permeable treatment walls, diversion ditches, sheet piling, and so forth. The licensee's design modifications should be developed through consideration of the results of the technical analyses. Remediation of the disposed waste may involve actions such as *in situ* stabilization of the wasteforms (e.g., grouting) and removal of a portion of or the entire unacceptable waste inventory for offsite disposal. The licensee should provide a technical basis that demonstrates 10 CFR 61.43 (i.e., protection of individuals during operations) will be met during remediation. They should develop a cost-benefit analysis to inform the selection of remedial actions.

A reviewer should evaluate the information provided by the licensee, including the technical basis for the proposed actions. The reviewer should evaluate the alternatives considered and the basis for the action selected. If design modifications are proposed, the reviewer should evaluate the technical basis for the performance of engineered barriers. The reviewer should determine if the licensee's desired performance of the engineered barriers is likely to be achieved. The reviewer should determine if the design modifications were developed in consultation with the results of the technical analyses. If remediation is selected, the reviewer should evaluate the basis for how much waste the licensee would remove and how the licensee would remove the waste. The technical basis demonstrating that 10 CFR 61.43 will be met should be reviewed. Finally, the reviewer should evaluate cost-benefit analyses that have been developed to ensure the mitigation activities are justified.

10.0 PERFORMANCE CONFIRMATION

Performance confirmation is the program of tests, experiments, and analyses that licensees conduct to evaluate and verify the accuracy of information used to demonstrate that the 10 CFR Part 61 performance objectives are met before disposal site closure. Prior to final closure of the disposal site, licensees are required by 10 CF 61.28 to submit an application to amend the license for closure. The closure application must include the specific details of the site closure plan. The plan must include additional geologic, hydrologic, and other disposal site data pertinent to the long-term containment of emplaced radioactive wastes obtained during the operational period. In addition, the plan must include the results of tests, experiments, or other analyses pertinent to the long-term containment of emplaced waste within the disposal site. Licensees must update the technical analyses for 10 CFR 61.13 using details of the final closure plan and the waste inventory. Although the terminology “performance confirmation” is not used in the regulation, as discussed below, the NRC staff believes that the elements of a performance confirmation program are supported by 10 CFR Part 61. Elements of performance confirmation may be completed during active operation as well as during the institutional control period. The following are the main elements of a performance confirmation program:

- verification that site conditions encountered during construction were within limits assumed during licensing
- verification that engineered barriers and other defense-in-depth protections were constructed as designed and will perform within limits assumed during licensing
- verification of the performance of natural barriers that were relied upon by the licensee in licensing to achieve compliance with the performance objectives
- monitoring of facility performance
- verification of the safety case

Performance confirmation is integrated with disposal system design, development, and construction to provide confidence that the disposal system will perform as intended. Performance confirmation can be used to supplement information satisfying the requirements of 10 CFR 61.28, 10 CFR 61.52, and 10 CFR 61.53.

The NRC staff expects that licensees may obtain additional geologic, hydrologic, or other disposal site data pertinent to the long-term containment of emplaced radioactive wastes during the operational period. In addition, monitoring of the performance of the disposal facility and minor custodial care is required for the duration of the institutional control period. Additional data with respect to facility performance and site conditions may be obtained during the institutional control period. Under 10 CFR 61.28 licensees are required to update technical analyses; the Commission will issue an amendment authorizing closure if the updated analyses demonstrate that the 10 CFR Part 61 performance objectives are met (e.g., performance assessment, intruder assessment, site stability evaluation, defense-in-depth analyses, protective assurance period analyses, and performance period analyses). A performance confirmation program can be used to proactively generate information to support updating the technical analyses for closure. The performance confirmation program can be designed to produce information to support the most risk-significant and uncertain elements of the technical analyses.

Table 10-1 Regulatory Requirements Supportive of Performance Confirmation

Section	Requirement
10 CFR 61.7(c)(3)	Post-closure monitoring and maintenance
10 CFR 61.12(g)	A description of the disposal site closure plan, including those features that facilitate closure and eliminate the need for maintenance
10 CFR 61.28	Contents of application for closure
10 CFR 61.52	Land disposal facility operation and disposal site closure
10 CFR 61.53(c)	Environmental monitoring during construction and operation
10 CFR 61.53(d)	Environmental monitoring, post operational surveillance

It is good practice for a licensee to update the technical analyses supporting licensing (e.g., performance assessment and intruder assessment) at regular intervals. Upon amending waste acceptance criteria to accept new waste, proposing changes to the design of the disposal site, or when new information about site characteristics or design properties becomes available, the licensee should determine if the site will continue to comply with the Subpart C performance objectives and, if necessary, update the analyses. While a regular interval for updating the technical analyses is not specified in the regulation, 10 CFR 61.58(f) requires licensees to annually review the content and implementation of their waste acceptance program. The purpose of this review, as described further in Section 9.4 of this document, is to ensure that the content of the waste acceptance program continues to be adequate and that the program is being implemented in a way that continues to protect public health and safety. As part of this annual review, licensees should also evaluate and document whether the waste acceptance criteria continues to provide reasonable assurance of compliance with the Subpart C performance objectives. If the evaluation finds that the waste acceptance criteria do not provide reasonable assurance of compliance with the Subpart C performance objectives, the licensee should submit the revised criteria and supporting technical analyses that demonstrate that the proposed criteria meet the performance objectives as part of a request for amendment to the license.

Updating technical analyses can ensure that appropriate operational practices (e.g., allowable limits) are identified and implemented to reduce the potential need for more challenging mitigation activities (e.g., installing new barriers, removing waste). Conditions that could trigger a decision to update waste acceptance criteria, and therefore to update technical analyses, may include but are not limited to the following:

(1) substantially different inventory than anticipated (e.g., quantity, concentration, form)
(2) new site information (e.g., environmental conditions, characterization data)
(3) new information on engineered barrier performance or other defense-in-depth protections
(4) monitoring data that are inconsistent with current analyses
(5) substantial changes to relevant scientific understanding
(6) use of updated dosimetry

Licensees should document the basis for their decision on whether the waste acceptance criteria and supporting technical analyses should be updated. The availability of new information may not always prompt a decision to update the waste acceptance criteria and supporting technical analyses. The operating period of a disposal facility may extend over multiple decades, and the NRC staff expects that new information will be developed. Regular updating is advised because it will allow a licensee to evaluate relevant information generated since the previous update. Regular updating will also reduce the likelihood that something unforeseen develops that calls into question the performance of the disposal facility. In some cases, significant information may become available to a licensee. The licensee should determine, in consultation with the pertinent regulator, if the new information warrants an update to the technical analyses.

Monitoring of environmental media is required by 10 CFR 61.53. Monitoring is required to provide early warning of release of radionuclides from the disposal site before they leave the site boundary. Most monitoring systems focus on sampling environmental media, such as groundwater or the atmosphere, some distance from the facility, such as within the buffer zone surrounding the facility or at the site boundary. It may be useful for a licensee to identify and use performance indicators. A performance indicator is a measure of the performance of subsystems of the disposal system that may be a precursor to the overall performance of the disposal system. Performance indicators may be a less direct measure of overall performance but have the advantage of providing early warning of changes in system performance. For example, monitoring of soil moisture underneath an engineered cover may provide an indication of increased infiltration that may lead to increased release of radioactivity from the disposal facility.

Licensees can use technical analyses supporting demonstration of compliance with the performance objectives to help determine what types of information would be most useful to monitor and when that information is significant. Monitoring data typically have moderate to significant variability. If monitoring data are used in performance confirmation, the NRC staff recommends that a licensee provide a description of the anticipated variability of monitoring data to help prevent misinterpretation of observational data. In some cases, a monitoring observation may appear to be an outlier. Licensees should not reject data as outliers without a statistical or physical basis. If a statistical basis cannot be provided, additional information should be collected. Reviewers should evaluate the technical basis for the treatment of outliers and determine if it is adequate. In some cases, a technical explanation may be available (e.g., the sample was contaminated). It is possible that initial information may appear to represent an outlier, however, in reality the observed behavior is not due to measurement error, for example, but rather represents complex, unanticipated phenomena. Licensees should use caution in dismissing outliers in observational data.

11.0 USE OF OTHER NRC GUIDANCE DOCUMENTS

The following tables are intended to provide references that may be useful to licensees in developing their technical analyses. Tables 11-1, 11-2, and 11-3 present references according to the performance objectives in 10 CFR Part 61. Table 11-4 provides a list of general topics and associated references. NUREG-1573 includes a bibliography of technical references applicable to LLW disposal (as of 2000) in its Appendices B and C (NRC, 2000a) that may also be useful to licensees and reviewers.

Table 11-1 Guidance Crosswalk for Performance Objective 10 CFR 61.41, Performance Assessment

Document	Description
NUREG-1573, "A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities" (NRC, 2000a)	Section 2, regulatory framework for 10 CFR Part 61
	Section 3.1, performance assessment approach
NUREG-1200, "Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility" (NRC, 1994)	Review procedures for technical analysis
NUREG-1757, "Consolidated Decommissioning Guidance" (NRC, 2006)	Volume 2, Section 3.5, evaluation of engineered barriers
NUREG/CR-5512, "Residual Radioactive Contamination from Decommissioning" (NRC, 1992)	Volume 1, Appendix E, Table E.6, solubility classes
NUREG-1854, "NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations" (NRC, 2007a)	Section 4.2, guidance on review of performance assessments for waste determinations, general technical review procedures

Table 11-2 Guidance Crosswalk for Performance Objective 10 CFR 61.42, Inadvertent Intruder Assessment

Document	Description
NUREG-1854, "NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations" (NRC, 2007a)[1]	Guidance on review of intruder analyses for waste determinations
NUREG-0782, "Draft Environmental Impact Statement on 10 CFR Part 61 Licensing Requirements for Land Disposal of Radioactive Waste" (NRC, 1981a) NUREG-0945 "Final Environmental Impact Statement on 10 CFR Part 61 Licensing Requirements for Land Disposal of Radioactive Waste" (NRC, 1982b) NUREG/CR-1759, "Data Base for Radioactive Waste Management" (directly supports NUREG-0782) (NRC, 1981b)	Describes the intruder assessment methodology used to develop waste classification tables in 10 CFR 61.55, including generic scenarios
Revised Draft Branch Technical Position on Concentration Averaging and Encapsulation, Rev. 1, May 2012 (NRC, 2012a)	Acceptable methods of concentration averaging
"Final Waste Classification and Waste Form Technical Position Papers," Rev. 0, May 11, 1983 (NRC, 1983d)	Guidance on classifying waste Various methods to determine radionuclide concentrations
"Technical Position on Waste Form (Revision 1)", January 18, 1991 (NRC, 1991b)	Guidance on wasteforms to comply with waste characteristics requirements in 10 CFR 61.56
NUREG-1573, "A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities" (NRC, 2000a)	Section 3.3, model abstractions for a performance assessment, generally applicable to intruder assessment

[1] Many of these references also apply to performance objective 10 CFR 61.41.

Table 11-2 Guidance Crosswalk for Performance Objective 10 CFR 61.42, Inadvertent Intruder Assessment

Document	Description
NUREG-1200, "Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility" (NRC, 1994)	Section 6.1, evaluation of pathways in total dose calculation
	Volume 2, Section 3.5.4, degradation mechanisms, capabilities of engineered barriers Volume 2, Section 3.5.5, summary of existing guidance and reference information for application of engineered barriers at disposal facilities
NUREG-1757, "Consolidated Decommissioning Guidance" (NRC, 2006)	Appendix M, Table M.5-M.12, water quality standards Appendix M.5, Potential sources of land use information
	Section I.6, selecting site-specific input parameters for models and providing a technical basis Section I.5, selection of codes/models and approaches for NRC acceptance of the codes/models
NUREG/CR-4370, "Update of Part 61 Impacts Analysis Methodology" (NRC, 1986a)	Provides scenarios and calculation approach to estimate intruder doses

Table 11-3 Guidance Crosswalk for Performance Objective 10 CFR 61.44, Site Stability Analysis

Document	Description
NUREG-1623, “Design of Erosion Protection for Long-Term Stabilization” (NRC, 2002b)	Design of erosion protection at uranium mill tailings sites Procedure for determining the suitability of a rock source
NUREG-1804, “Yucca Mountain Review Plan” (NRC, 2003c)	Seismic events in waste disposal
NUREG-1200, “Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility” (NRC, 1994)	Site stability analysis for long-lived waste
NUREG-1757, “Consolidated Decommissioning Guidance” (NRC, 2006)	Section 3.5, risk-informed approach to engineered barriers
	Analogs for wasteform stability
	Durability of earthen covers
	Section 3.5.5, reference information regarding engineered cover design and performance
	Appendix P, evaluations of rock durability
NUREG/CR-2642, “Long-Term Survivability of Riprap for Armoring Uranium Mill Tailings and Covers” (NRC, 1982c)	Table 6.7, comparative data on natural materials
	Appendix A, information on rock weathering, durability, examples of analogs
Technical Position on Waste Form (Revision 1) (NRC, 1991b)	Specific test procedures and criteria to evaluate wasteform stability
NUREG-0902, “Site Suitability, Selection and Characterization, BTP – Low-Level Waste Branch” (NRC, 1982e)	Provides additional information on processes to be avoided that may affect site stability

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
Analysis Timeframe	NUREG-1573, "A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities" (NRC, 2000a) "Technical Analysis Supporting Definition of Period of Performance for Low-Level Waste Disposal" (NRC, 2011c)
Radon Diffusion and Barriers	Regulatory Guide 3.64, "Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers" (NRC, 1989a) NUREG/CR-4370, "Update of Part 61 Impacts Analysis Methodology" (NRC, 1986a)
Sensitivity/Uncertainty Analysis	NUREG-1757, "Consolidated Decommissioning Guidance," Vol. 2, Appendix I, Section 1.7 (NRC, 2006) NUREG-1573, Section 3.3.2 (NRC, 2000a)
Expert Elicitation and Judgment	NUREG-1563, "Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program" (NRC, 1996)
Modelling Climate and Infiltration	NUREG-1573, Section 3.3.3 (NRC, 2000a) NUREG-1854, Section 4.3.1 (NRC, 2007a)

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
Waste Acceptance Criteria	Revised Draft Branch Technical Position on Concentration Averaging and Encapsulation, Rev. 1, May 2012 (NRC, 2012a) Final Waste Classification and Waste Form Technical Position Papers," Rev. 0, May 11, 1983 (NRC, 1983d) Technical Position on Waste Form, Rev. 1 (NRC, 1991b) NUREG-1200, SRP 4.1, SRP 6.11 (NRC, 1994)
Waste Characterization	See Waste Acceptance Criteria (NRC, 1983d); (NRC, 2012a); (NRC, 1991b) NUREG/CR-6567, "Low-Level Radioactive Waste Classification, Characterization, and Assessment: Waste Streams and Neutron-Activitated Metals." (NRC, 2000b) NUREG-1575, "Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME)," Supplement 1 (NRC, 2009) NUREG-1576, "Multi-Agency Radiological Laboratory Analytical Protocols Manual (MARLAP)" (NRC, 2004b) NUREG-1200, SRP 8.6, SRP 9.1 (NRC, 1994)

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
Waste Certification	NUREG-1200, SRP 8.5 (NRC, 1994) NUREG/BR-0204, “Instructions for Completing NRC’s Uniform Low-Level Radioactive Waste Manifest”, Revision 2, July 1998 (NRC, 1998)
Source Term Modelling	NUREG-1573, Section 3.3.5 (NRC, 2000a) NUREG-1854, Section 4.3.3 (NRC, 2007a)
Inventory Abstraction	NUREG-1573, Sections 3.3.5.1, 3.3.5.2, and 3.3.5.7 (NRC, 2000a) NUREG-1854, Sections 3.1 and 4.3.3.1.1 (NRC, 2007a)
Chemical Environment and Abstraction	NUREG-1573, Section 3.3.5.6 (NRC, 2000a) NUREG-1854, Section 4.3.3.1.4 (NRC, 2007a) NUREG-1804, “Yucca Mountain Review Plan,” Section 4.2.1.3.3 (NRC, 2003c)
Waste Containers, Wasteform, and Waste Type Wasteforms and Degradation	NUREG-1573, Section 3.3.5.4 (NRC, 2000a) NUREG-1854, Section 4.3.3.1.2 (NRC, 2007a)
Engineered Barriers	NUREG-1573, Section 3.3.4 (NRC, 2000a) NUREG-1854, Section 4.3.2 (NRC, 2007a) NUREG-1804, Sections 4.2.1.3.1 and 4.2.1.3.2 (NRC,

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
	2003c)
Aqueous Release Models	NUREG-1854, Section 4.3.3.2 (NRC, 2007a) NUREG-1804, Section 4.3.1.2.4 (NRC, 2003c)
Gaseous Release Screening, Processes Generating Gases	NUREG-1573, Sections 3.3.5.7.1 and 3.3.5.7.2 (NRC, 2000a)
Climate and Infiltration Modelling	NUREG-1573, Section 3.3.3 (NRC, 2000a) NUREG-1854, Section 4.3.1(NRC, 2007a)
Biosphere Characteristics and Dose Modelling	NUREG-1573, Section 3.3.7 (NRC, 2000a) NUREG-1854, Section 4.3.5 (NRC, 2007a)
Transport Modelling	NUREG-1573, Section 3.3.6 (NRC, 2000a) NUREG-1854, Section 4.3.4 (NRC, 2007a)
Groundwater Transport	NUREG-1573, Section 3.3.6.1.2 (NRC, 2000a)
Surface Water Transport	NUREG-1573, Section 3.3.6.2 (NRC, 2000a) NUREG-1854, Section 4.3.4.1.2 (NRC, 2007a)
Atmospheric Transport	NUREG-1573, Sections 3.3.6.3.2.1 and 3.3.6.3.2 (NRC, 2000a)

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
Development of a License Application for an LLW Disposal Facility	NUREG-1199, "Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility," Revision 2 (NRC, 1991a) Regulatory Guide 4.18, "Standard Format and Content of Environmental Reports for Near-Surface Disposal of Radioactive Waste" (NRC, 1983e). NUREG-1300, "Environmental Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility" (NRC, 1987)
Environmental Monitoring	NUREG-1388, "Environmental Monitoring of Low-Level Radioactive Waste Disposal Facility" (NRC, 1989e)
Alternate Disposal Methods	NUREG-1241, "Licensing of Alternative Methods of Disposal of Low-Level Radioactive Waste" (NRC, 1986c)
Site Selection	NUREG-0902, "Site Suitability, Selection and Characterization, BTP – Low-Level Waste Branch" (NRC, 1982e) Regulatory Guide, 4.19, "Guidance for Selecting Sites for Near-Surface Disposal of Low-Level Radioactive Waste" (NRC, 1988b)
Scenario Development	NUREG/CR-5927, Vol. 1, (SAND91-2802), "Evaluation of a Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities: Evaluation of Modeling Approaches," (NRC, 1993a)

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
	NUREG-1200, Section 2.4.1, Appendix A (NRC, 1994) NUREG-1199, "Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility," Revision 2 (NRC, 1991a) NUREG-1623, "Design of Erosion Protection for Long-Term Stabilization," (NRC, 2002b)

12.0 REFERENCES

The references cited in the following list generated by the NRC or NRC contractor are available either in the NRC Agencywide Documents Access and Management System (ADAMS) or the Public Document Room. Accession numbers for ADAMS or the Public Legacy Library are provided where available.

Albright et al., 2004. W.C., C.H. Benson, G.W. Gee, A.C. Roesler, T. Abichou, P. Apiwantragoon, B.F. Lyles, and S.A. Rock, "Field water balance of landfill final covers," *Journal of Environmental Quaity.* **33**:2317-2332.

Albright et al., 2006a. Albright, W., Benson, C., Gee, G., Abichou, T., McDonald, E., Tyler, S., and Rock, S, "Field Performance of a compacted clay landfill final cover at a humid site," Journal *of Geotechnical and Geoenvironmental Engineering*, 132(11), 1393-1403.

Albright et al., 2006b. Albright, W., Benson, C., Gee, G., Abichou, T., Tyler, S., and Rock, S., "Field performance of three compacted clay landfill covers," *Vadose Zone Journal*, 5(4), 1157-1171.

Allaire et al., 2008. Allaire, S.E., J.A. Lafond, A.R. Cabral, and S.F. Lange, "Measurement of Gas Diffusion through Soils: Comparison of Laboratory Methods," *Journal of Environmental Monitoring*, 10: 1326–1336, 2008.

Alley, 2000. Alley, R.B., "Ice-core evidence of abrupt climate changes," Proceedings of the National Academy of Sciences, Vol 97, no. 4, pp 1331-1334, 2000.

ANS, 2008, American Nuclear Society, "Measurement of the Leachability of Solidified Low-Level Radioactive Wastes by a Short-term Test Procedure," ANSI/ANS-16.1-2003, La Grange Park, IL, 2003 (reapproved 2008).

ASTM, 2009, ASTM Standard C1308-08, "Standard Test Method for Accelerated Leach Test for Diffusive Releases from Solidified Waste and a Computer Program to Model Diffusive, Fractional Leaching from Cylindrical Waste Forms," ASTM International, West Conshohocken, PA, 2009.

Anderson and Anderson, 2010. Anderson, R.S., and S.P. Anderson, *Geomorphology: The Mechanics and Chemistry of Landscapes*, Cambridge University Press, Cambridge, UK, 2010.

Baes et al., 1984. Baes, C.F., R.D. Sharp, A.L. Sjoreen, and R.W. Shor, "A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture," ORNL-5786, Oak Ridge National Laboratory, Oak Ridge, TN, 1984.

Bear, 1979. Bear, J., *Hydraulics of Groundwater,* McGraw-Hill, New York, NY, 1979.

Bear and Verruijt, 1987. Bear, J., and A. Verruijt, *Modeling Groundwater Flow and Pollution: With Computer Programs for Sample Cases,* Springer, New York, NY, 1987.

Benson et al., 2011. Benson, C.H. et al., “Engineered Covers for Waste Containment: Changes in Engineering Properties and Implications for Long-Term Performance Assessment,” NUREG/CR-7028, Volume 1, US Nuclear Regulatory Commission, Washington DC, 2011.

Bethke and Yeakel, 2009a. Bethke, C.M., and S. Yeakel, “The Geochemists Workbench®, Release 8.0, GWB Essentials Guide,” University of Illinois, Urbana, IL, 2009.

Bethke and Yeakel, 2009b. Bethke, C.M., and S. Yeakel, “The Geochemists Workbench®, Release 8.0, Reaction Modeling Guide,” University of Illinois, Urbana, IL, 2009.

Bethke and Yeakel, 2009c. Bethke, C.M., and S. Yeakel, “The Geochemists Workbench®, Release 8.0, Reactive Transport Modeling Guide,” University of Illinois, Urbana, IL, 2009.

Bethke and Yeakel, 2009d. Bethke, C.M., and S. Yeakel, “The Geochemists Workbench®, Release 8.0, Reference Manual,” University of Illinois, Urbana, IL, 2009.

BIOMOVS II, 1996. BIOspheric MOdel Validation Study - Phase II, "Development of a Reference Biospheres Methodology for Radioactive Waste Disposal, Final Report of the Reference Biospheres Working Group," BIOMOVS II Technical Report No. 6, September 1996.

Bodvarsson et al., 2000. Bodvarsson, G., S. Finsterle, H.H. Liu, C.M. Oldenburg, K. Pruess, E. Sonnenthal, and Y-S. Wu, “Flow and Transport Modeling of the Vadose Zone,” in *Vadose Zone Science and Technology Solutions*, Volume II, Chapter 5, B.B. Looney and R.W. Falta, eds., Battelle Press, Columbus, OH, 2000.

Bonano and Cranwell, 1988. Bonano, E.J. and R.M. Cranwell, “Treatment of uncertainties in the performance assessment of geologic high-level radioactive waste repositories,” Journal International Association Mathematical Geology, 20:543-565, 1988.

Bracke and Müller, 2008. Bracke, G., and W. Müller, “Contribution to a More Realistic Approach in Assessing the Release of C-14 from Low-Level Radioactive Waste Repositories,” *Journal of Contaminant Hydrology*, 102: 210–216, 2008.

Brock and Sherbirni, 2012. Brock, T. A., and S. S. Sherbini, “Principles in Practice: Radiation Regulation and the NRC,” Bulletin of the Atomic Scientists, **68**(3) pp36-43, 2012.

Brookins, 1984. Brookins, D.G., *Geochemical Aspects of Radioactive Waste Disposal*, Springer-Verlag, New York, NY, 1984.

Buckingham, 1904. Buckingham, E., “Contributions to Our Knowledge of the Aeration of Soils,” U.S. Department of Agriculture Bureau of Soils Bulletin 25, Washington, DC, 1904.

Bullard, 1986. Bullard, K.L., “Comparison of Estimated Probable Maximum Flood Peaks with Historic Floods,” Engineering and Research Center, U.S. Department of the Interior, Denver, CO, 1986.

Colman and Dethier, 1986. Colman, S.M., and D.P. Dethier, eds., *Rates of Chemical Weathering of Rocks and Minerals*, Academic Press, Inc., Orlando, FL, 1986.

Crawford et al., 2008. Crawford, T.V., C.W. Miller, and A.H. Weber, “Atmospheric Transport of Radionuclides,” in *Radiological Risk Assessment and Environmental Analysis*, Chapter 3, J.E. Till and H.A. Grogan, eds., Oxford University Press, Oxford, UK, 2008.

Crippen and Bue, 1977. Crippen, J.R., and C.D. Bue, “Maximum Floodflows in the Conterminous United States,” U.S. Geological Survey Water Supply Paper 1887, Washington, DC, 1977.

Culot et al., 1976. Culot, M.V.J., H.G. Olson, and K.J. Schiager, “Effective Diffusion Coefficient of Radon in Concrete, Theory and Method for Field Measurements,” in *Health Physics,* 30: 263-270,1976.

Cunningham and Williams, 1980. Cunningham, R.E., and R.J.J. Williams, *Diffusion in Gases and Porous Media*, Plenum Press, New York, NY, 1980.

Daveler and Wolery, 1992. Daveler, S.A., and T.J. Wolery, “EQPT, a Data File Preprocessor for the EQ3/6 Software Package: User’s Guide and Related Documentation (Version 7.0),” UCLRL-MA-110662, Part II, Lawrence Livermore National Laboratory, Livermore, CA, 1992.

Domenico and Schwartz, 1998. Domenico, P.A., and F.W. Schwartz, *Physical and Chemical Hydrogeology*, 2nd ed., John Wiley and Sons, New York, NY, 1998.

Dorn, R.I., “Boulder Weathering and Erosion Associated with a Wildfire, Sierra Ancha Mountains, Arizona,” *Geomorphology*, **55**: 155-171, 2003.

Drever and Clow, 1995. Drever, J.I., and D.W. Clow, “Weathering Rates in Catchments,” In *Reviews in Mineralogy Vol. 31: Chemical Weathering Rates of Silicate Minerals*, A.F. White and S.L. Brantley, eds., Mineralogical Society of America, Washington, DC, 1995.

Eisenberg et al., 1999. Eisenberg, N.A., M.P. Lee, T.J. McCartin, K.I. McConnell, M. Thaggard, and A.C. Campbell, “Development of a Performance Assessment Capability in the Waste Management Programs of the U.S. Nuclear Regulatory Commission,” *Risk Analysis*, 19(5): 847–876, October 1999, ADAMS Accession No. ML031750717.

Eisenberg and Sagar, 2000. Eisenberg, N.A. and B. Sagar, “Importance Measures for Nuclear Waste Repositories,” Reliability Engineering and System Safety 70(3): 217-239, 2000, ADAMS Accession No. ML061370360.

EPA, 1988. U.S. Environmental Protection Agency, “Federal Guidance Report No. 11: Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion,” EPA-520/1-88-020, Washington, DC, September 1988.

EPA, 1991. U.S. Environmental Protection Agency, “MINTEQA2/PRODEFA2, a Geochemical Assessment Model for Environmental Systems: Version 3.0 User’s Manual,” EPA/600/3-91/021, Environmental Research Laboratory, Athens, GA, 1991.

EPA, 1993. U.S. Environmental Protection Agency, “Federal Guidance Report No. 12: External Exposure to Radionuclides in Air, Water and Soil,” EPA-402-R-93-081, Washington, DC, September 1993.

EPA, 1999. U.S. Environmental Protection Agency, “Federal Guidance Report No. 13: Cancer Risk Coefficients for Environmental Exposure to Radionuclides,” EPA 402-R-99-001, Washington, DC, September 1999.

EPA, 2006. U.S. Environmental Protection Agency, “Guidance on Systematic Planning Using the Data Quality Objectives Process,” EPA/240/B-06/001, February 2006.

Esh et al., 2001. Esh, D.W., R.B. Codell, T.J. McCartin, and B.W. Leslie, “Repository Importance Analyses,” Proceedings of the 2001 International High-Level Radioactive Waste Management Conference, Las Vegas, NV, April 29–May 3, American Nuclear Society, La Grange Park, IL, 2001.

EC, 2009a. European Commission, "Trial of formal Use of Expert Judgement for Scenario Conceptualisation Milestone," PAMINA: Performance Assessment Methodologies in Application to Guide the Development of the Safety, D-No: 2.2.C.3, Brussels, 2009.

EC, 2009b. European Commission, "Scenario Uncertainty," PAMINA: Performance Assessment Methodologies in Application to Guide the Development of the Safety, D-No: 2.2.C.1, Brussels, 2009.

EC, 2009c. European Commission, "Report on Scenario Development," PAMINA: Performance Assessment Methodologies in Application to Guide the Development of the Safety, D-No: 3.1.1, Brussels, 2009.

Evans et al., 2001. Evans, D.D., T.J. Nicholson, and T.C. Rasmussen, eds., *Flow and Transport through Unsaturated Fractured Rock*, 2nd ed., Geophysical Monograph Series 42, American Geophysical Union, Washington, DC, 2001.

Farber and Hemmersbaugh, 1993. Farber, D. A. and P. A. Hemmersbaugh, “The Shadow of the Future: Discount Rates, Later Generations, and the Environment,” *Vanderbilt Law Review*, **46**, pp. 267-304, 1993.

Faybishenko et al., 2000. Faybishenko, B., P.A. Witherspoon, and S.M. Benson, eds., *Dynamics of Fluids in Fractured Rock*, Geophysical Monograph Series 122, American Geophysical Union, Washington, DC, 2000.

Finkel, 1990. Finkel, A. M., "Confronting Uncertainty in Risk Management," Center for Risk Management, Resources for the Future, Washington, DC, 1990.

Freeze and Cherry, 1979. Freeze, R.A., and J.A. Cherry, *Groundwater,* Prentice-Hall, Inc., Englewood Cliffs, NJ, 1979.

Fricke et al., 1993. Fricke, H.C., W.C. Clyde, J.R. O’Neil, P.D. Gingerich, “Evidence for rapid climate change in North America during the latest Paleocene thermal maximum: oxygen isotope compositions of biogenic phosphate from the Bighorn Basin (Wyoming),” Earth and Planetary Science Letters 160, pp 193-208, 1993.

Giglio et al., 2013. Giglio, S., Maggiori, M., and J. Stroebel, “Very Long-Run Discount Rates,” Booth School of Business, University of Chicago, NBER, 2013.

Gornitz, 2007. Gornitz, Vivien,“Sea Level Rise, After the Ice Melted and Today,” Goddard Institute for Space Studies, National Aeronautics and Space Administration, January 2007. http://www.giss.nasa.gov/research/briefs/gornitz_09

Hillel, 1980. Hillel, D., *Fundamentals of Soil Physics,* Academic Press, New York, NY, 1980.

Hommel, 2012. Hommel, S., "Features, Events, and Processes for Liquid Waste Performance Assessments", Savannah River Remediation LLC, SRR-CWDA-2012-00011, Rev. 0, February 14, 2012.

IAEA, 1994. International Atomic Energy Agency, “Handbook of Parameter Values for the Prediction of Coefficients: Workers and Members Radionuclide Transfer in Temperate Environments,” Technical Report Series No. 364, Vienna, 1994.

IAEA, 1996. International Atomic Energy Agency, “Requirements and methods for low and intermediate level waste package acceptability,” IAEA-TECDOC-864, Vienna, February 1996.

IAEA, 2000. International Atomic Energy Agency, “Inspection and verification of waste packages for near surface disposal,” IAEA-TECDOC-1129, Vienna, January 2000.

IAEA, 2003. International Atomic Energy Agency, "Reference Biospheres for Solid Radioactive Waste Disposal: Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme," BIOMASS, IAEA-BIOMASS-6, Vienna, July 2003.

IAEA, 2004. International Atomic Energy Agency, "Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM), Vol. I – Review and Enhancement of Safety Assessment Approaches and Tools; Vol. II – Tests Cases," Vienna, 2004.

IAEA, 2007. International Atomic Energy Agency, “Strategy and Methodology for Radioactive Waste Characterization,” IAEA-TECDOC-1537, Vienna, March 2007.

IAEA, 2008. International Atomic Energy Agency, “The Management System for the Disposal of Radioactive Waste,” IAEA Safety Standard Series No. GS-G-3.4, Vienna, 2008.

IAEA, 2009. International Atomic Energy Agency, “Determination and Use of Scaling Factors for Waste Characterization in Nuclear Power Plants,” IAEA Nuclear Energy Series No. NW-T-1.18, Vienna, April 2009.

IAEA, 2011. International Atomic Energy Agency, “Disposal of Radioactive Waste Specific Safety Requirements,” IAEA Safety Standards Series SSR-5, Vienna, 2011.

IAEA, 2012. International Atomic Energy Agency, “The Safety Case And Safety Assessment For The Disposal Of Radioactive Waste Specific Safety Guide,” IAEA Safety Standards Series No. SSG-23, Vienna, 2012.

ICRP, 1977. International Commission on Radiological Protection, “Recommendations of the ICRP,” Publication 26, Annals of the ICRP 1 (3).

ICRP, 1979. International Commission on Radiological Protection, “Limits for Intakes of Radionuclides by Workers,” Publication 30 (Part 1), Annals of the ICRP 2 (3-4).

ICRP, 1980. International Commission on Radiological Protection, “Limits for Intakes of Radionuclides by Workers,” Publication 30 (Part 2), Annals of the ICRP Volume 4/3-4.

ICRP, 1982. International Commission on Radiological Protection, “Limits for Intakes of Radionuclides by Workers,” Publication 30 (Part 3), Annals of the ICRP Volume 6/2-3.

ICRP, 1991. International Commission on Radiological Protection, “1990 Recommendations of the International Commission on Radiological Protection,” Publication 60, Annals of the ICRP 21 (1-3).

ICRP, 1996. International Commission on Radiological Protection, “Age-Dependent Doses to the Members of the Public from Intake of Radionuclides, Part 5, Compilation of Ingestion and Inhalation Coefficients,” Publication 72, September 1996.

ICRP, 2007. International Commission on Radiological Protection, “The 2007 Recommendations of the International Commission on Radiological Protection,” Publication 103, Annals of the ICRP 37 (2-4), 2007.

IPCC, 2001. Intergovernmental Panel on Climate Change - Third Assessment Report, “Climate Change 2001,” GRID-Arendal, United Nations Environment Programme. http://www.grida.no/publications/other/ipcc_tar/?src=/climate/ipcc_tar/wg1/fig11-4.htm

Jenhyns, 2003. Jenkyns, H.C., “Evidence for rapid climate change in the Mesozoic-Palaeogene greenhouse world,” *Phil. Trans. R. Soc. Lond. A*, 361, 2003.

Klinger and England, 2013. Klinger, R., and England, J., "Paleoflood Studies and their Application to Reclamation Dam Safety," Presentation for the "Workshop on Probabilistic Flood Hazard Assessement (PFHA)," U.S. Nuclear Regulatory Commission, Rockville, MD, January 29 –31, 2013.

Kondolf and Piégay, 2005. Kondolf, G.M., and H. Piégay, eds., *Tools in Fluvial Geomorphology*, John Wiley & Sons, Ltd, Chichester, UK, 2005.

Koutsoyiannis, 1999. Koutsoyiannis, D., “A Probabilistic View of Hershfield’s Method for Estimating Probable Maximum Precipitation,” *Water Resources Research*, 35(4): 1313–1322, 1999.

Kristensen et al., 2010. Kristensen, A.H., A. Thorbjørn, M.P. Jensen, M. Pedersen, and P. Moldrup, "Gas-Phase Diffusivity and Tortuosity of Structured Soils," *Journal of Contaminant Hydrology*, 115: 26–33, 2010.

Ledoux and deMarsily, 1997. Ledoux, E., and G. deMarsily, "Variability in Natural Systems and Means to Characterise It," *Effects of Spatial Variability on Radionuclide Migration*, Workshop Proceedings, Paris, France, June 9–11, 1997, pp. 59-71, Nuclear Energy Agency/Organisation for Economic Co-Operation and Development, Paris, France, 1997.

Looney and Falta, 2000. Looney, B.B., and R.B. Falta, *Vadose Zone Science and Technology Solutions,* Battelle Press, Columbus, OH, 2000.

Meyer et al., 1999. Meyer, P.D., G.W. Gee, M.L. Rockhold, and M.G. Scap, "Characterization of Soil Hydraulic Parameter Uncertainty," in *Proceedings of the International Workshop on Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media*, pp. 1439–1451, M.Th. van Genuchten, F.J. Leij, and L.J. Wu, eds., University of California Riverside Press, Riverside, CA, 1999.

Millington, 1959. Millington, R.J., "Gas Diffusion in Porous Media," *Science*, 130: 100–102, 1959.

Millington and Quirk, 1960. Millington, R.J., and J.P. Quirk, "Transport in Porous Media," *Transactions of the 7th International Congress of Soil Science*, Vol. 1, pp. 97–106, 1960.

Moldrup et al., 2004. Moldrup, P., T. Olesen, S. Yoshikawa, T. Komatsu, and D.E. Rolston, "Three-Porosity Model for Predicting the Gas Diffusion Coefficient in Undisturbed Soil," *Soil Science Society of America Journal*, 68: 750–759, 2004.

NAS/NRC, 1990. National Academy of Sciences/National Research Council, *Ground Water Models: Scientific and Regulatory Applications,* National Academy Press, Washington, DC, 1990.

NAS/NRC, 2001. National Academy of Sciences/National Research Council*, Conceptual Models of Flow and Transport in the Fractured Vadose Zone,* National Academy Press, Washington, DC, 2001.

NAS/NRC, 2007. National Academy of Sciences/National Research Council*, Assessing the Performance of Engineered Waste Containment Systems,* National Academy Press, Washington, DC, 2007.

Nazaroff et al., 1988. Nazaroff, W.W., et al., "Soil as a Source of Indoor Radon: Generation, Migration, and Entry," in *Radon and Its Decay Products in Indoor Air*, W.W. Nazaroff and A.V. Nero, eds., John Wiley & Sons, New York, NY, 1988.

Nazaroff, 1992. Nazaroff, W.W., "Radon Transport from Soil to Air," *Reviews of Geophysics*, 30(2): 137–160, 1992.

NCRP, 1984. National Council on Radiation Protection and Measurements, “Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment,” NCRP Report No. 76, NCRP, Bethesda, MD, 1984.

NCRP, 1995. National Council on Radiation Protection and Measurements, “Principles and Applications of Collective Dose in Radiation Protection,” NCRP Report No. 121, Bethesda, MD, 1995.

NCRP, 1996a. National Council on Radiation Protection and Measurements, “Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground,” NCRP Report No. 123, Vol. I, Bethesda, MD, 1996.

NCRP, 1996b. National Council on Radiation Protection and Measurements, “Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground—Worksheets,” NCRP Report No. 123, Vol. II, NCRP, Bethesda, MD, 1996.

NCRP, 2005. National Council on Radiation Protection and Measurements, “Performance Assessment of Near-Surface Facilities for Disposal of Low-Level Radioactive Waste,” NCRP Report No. 152, Bethesda, MD, December 31, 2005.

Newell and Pizer, 2003. Newell, Richard G. and W. A. Pizer, “Discounting the distant future: how much do uncertain rates increase valuations,” Journal of Environmental Economics and Management **46**, pp. 52-71, 2003.

Neuman, 1990. Neuman, S., “Universal Scaling of Hydraulic Conductivities and Dispersivities in Geologic Media,” *Water Resources Research,* 26(8): 1749–58, 1990.

Nielson et al., 1984. Nielson, K.K., V.C. Rogers, and G.W. Gee, “Diffusion of Radon through Soils: A Pore Distribution Model,” *Soil Science Society of America Journal*, 48: 482–487, 1984.

Nielsen et al., 1986. Nielsen, D.R., M.T. Van Genuchten, and J.W. Biggar, “Water Flow and Solute Transport Processes in the Unsaturated Zone,” *Water Resources Research*, 22: 89S–108S, 1986.

Nielson and Rogers, 1988. Nielson, K.K., and V.C. Rogers, “Radon Emanation and Transport in Porous Media,” *Proceedings: 1988 Symposium on Radon and Radon Reduction Technology,* October 17-21, 1988, Vol. 1, U.S. Environmental Protection Agency, Denver, CO, 1988.

NEA, 1992. Nuclear Energy Agency, "Safety Assessment of Radioactive Waste Repositories: Systematic Approaches to Scenario Development, Report of the NEA Working Group on the Identification and Selection of Scenarios for the Safety Assessment of Radioactive Waste Disposal," OECD Nuclear Energy Agency, Paris, 1992.

NEA, 2001. Nuclear Energy Agency, "Methods Scenario Development Methods and Practice: An Evaluation Based on the NEA Workshop on Scenario Development, Madrid, Spain, May 1999," OECD, Paris, 2001.

NEA, 2002. Nuclear Energy Agency, "Features, Events and Processes (FEPs) for Geological Disposal of Radioactive Waste: An International Database," OECD, Radioactive Waste Management, 2002.

NEA, 2012. Nuclear Energy Agency, "Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste: Outcomes of the NEA MeSA Initiative," Organisation for Economic Co-operation and Development, Radioactive Waste Management, 2012.

NEA/OECD, 2001. Nuclear Energy Agency/Organisation for Economic Co-operation and Development, "Gas Generation and Migration in Radioactive Waste Disposal: Safety-Relevant Issues," Workshop Proceedings, Reims, France, June 26–28, 2000, NEA/OECD, Paris, France, 2001.

NOAA, 2008. NOAA Paleoclimatology, National Climatic Data Center, National Oceanic and Atmospheric Administration, "Glacial and Interglacial Scale (<105 Years)," NOAA Paleoclimatology, National Climatic Data Center, National Oceanic and Atmospheric Administration, August 20, 2008. http://www.ncdc.noaa.gov/paleo/ctl/clisci100k.html

NRC, 1977. U.S. Nuclear Regulatory Commission, "Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50 Appendix I," Regulatory Guide 1.109, Rev. 1, Washington, DC, October 1977, ADAMS Accession No. ML003740384.

NRC, 1981a. U.S. Nuclear Regulatory Commission, "Draft Environmental Impact Statement on 10 CFR Part 61 Licensing Requirements for Land Disposal of Radioactive Waste," NUREG-0782, 4 Vols., Washington, DC, September 1981, ADAMS Accession Nos. ML052590347, ML052590350, ML052590353, and ML052590354.

NRC, 1981b. U.S. Nuclear Regulatory Commission, "Data Base for Radioactive Waste Management, Review of Low-Level Radioactive Waste Disposal History," NUREG/CR-1759, Vol. 1, November 1981, ADAMS Accession No. ML092010353.

NRC, 1982a. U.S. Nuclear Regulatory Commission, "Licensing Requirements for Land Disposal of Radioactive Waste: Final Rule," *Federal Register*, Vol. 47, No. 248, pp. 57446–57482, December 27, 1982.

NRC, 1982b. U.S. Nuclear Regulatory Commission, "Final Environmental Impact Statement on 10 CFR Part 61 Licensing Requirements for Land Disposal of Radioactive Waste," NUREG-0945, 3 Vols., Washington, DC, November 1982, ADAMS Accession Nos. ML052590184, ML052920727, and ML052590187.

NRC, 1982c. U.S. Nuclear Regulatory Commission (Lindsey et al., Jahns, R.H.), "Long-Term Survivability of Riprap for Armoring Uranium Mill Tailings and Covers: A Literature Review," NUREG/CR-2642 (PNL-4225), Washington, DC, 1982, Public Legacy Library Accession No. 8207140120, Microform 13845:347-13846:124.

NRC, 1982d. U.S. Nuclear Regulatory Commission (McKenzie, D.H., L.L. Cadwell, C.E. Cushing, Jr., R. Harty, W.E. Kennedy, Jr., M.A. Simmons, J.K. Soldat, and B. Swartzman), "Relevance of Biotic Pathways to the Long-Term Regulation of Nuclear-Waste Disposal: A

Report on Tasks 1 and 2 of Phase 1," NUREG/CR-2675, Vol. 1, National Technical Information Service, Springfield, VA, 1982, Public Legacy Library Accession No. 8208180126, Microform 14391:289-14391:361.

NRC, 1982e. U.S. Nuclear Regulatory Commission, "Site Suitability, Selection and Characterization, BTP – Low-Level Waste Branch," NUREG-0902, April 1982, ADAMS Accession No. ML053010325.

NRC, 1983a. U.S. Nuclear Regulatory Commission, "Influence of Cover Defects on the Attenuation of Radon with Earthen Cover," NUREG/CR-3395, Public Legacy Library Accession No. 8312020113, Microform 21367:292-21367:326.

NRC, 1983b. U.S. Nuclear Regulatory Commission (Vorhees, L.D., M.J. Sale, J.W. Webb, and P.J. Mulholland), "Guidance for Disposal of Uranium Mill Tailings: Long-Term Stabilization of Earthen Cover Materials," NUREG/CR-3199 (ORNL/TM-8685), Public Legacy Library Accession No. 8310260423, Microform: 20926:016-20926:123.

NRC, 1983c. U.S. Nuclear Regulatory Commission (Schumm, S.A., and P.J. Chorley), "Geomorphic Controls on the Management of Nuclear Waste," NUREG/CR-3276RW, Public Legacy Library Accession No. 8311080172, Microform 21091:001-21091:151.

NRC, 1983d. U.S. Nuclear Regulatory Commission, "Final Waste Classification and Waste Form Technical Position Papers," Rev. 0, Washington, DC, May 11, 1983, ADAMS Accession No. ML033630755.

NRC, 1983e. U.S. Nuclear Regulatory Commission, "Standard Format and Content of Environmental Reports for Near-Surface Disposal of Radioactive Waste," Regulatory Guide 4.18, June 1983, ADAMS Accession No. ML003739515.

NRC, 1984. U.S. Nuclear Regulatory Commission, "Radon Attenuation Handbook for Uranium Mill Tailings Cover Design," NUREG/CR-3533, ADAMS Accession No. Public Legacy Library Accession No. 8405210555, Microform 24529:119-24529:207.

NRC, 1986a. U.S. Nuclear Regulatory Commission, "Update of Part 61 Impacts Analysis Methodology," NUREG/CR-4370, 2 Vols., Washington, DC, January 1986, ADAMS Accession Nos. ML100251399, ML100250917.

NRC, 1986b. U.S. Nuclear Regulatory Commission, "Low-Level Radioactive Waste Scaling Factors, 10 CFR Part 61," Information Notice No. 86-20, March 28, 1986, ADAMS Accession No. ML031220625.

NRC, 1986c. U.S. Nuclear Regulatory Commission, "Licensing of Alternative Methods of Disposal of Low-Level Radioactive Waste," NUREG-1241, December 1986, ADAMS Accession No. ML053010322.

NRC, 1987. U.S. Nuclear Regulatory Commission, "Environmental Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility," NUREG-1300, April 1987, ADAMS Accession No. ML053010347.

NRC, 1988a. U.S. Nuclear Regulatory Commission, “Generic Technical Position on Peer-Review for High-Level Nuclear Waste Repositories,” NUREG-1297, Washington, DC, February 1988, ADAMS Accession No. ML033160259.

NRC, 1988b. U.S. Nuclear Regulatory Commission, “Guidance for Selecting Sites for Near-Surface Disposal of Low-Level Radioactive Waste,” Regulatory Guide 4.19, August 1988, ADAMS Accession No. ML003739520.

NRC, 1989a. U.S. Nuclear Regulatory Commission, “Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers,” Regulatory Guide 3.64, Washington, DC, 1989, ADAMS Accession No. ML003739876.

NRC, 1989b. U.S. Nuclear Regulatory Commission (Shipers), “Background Information for the Development of a Low-Level Waste Performance Assessment Methodology, Identification of Potential Exposure Pathways,” NUREG/CR-5453, Vol. 1, Public Legacy Library Accession No. 9001100240, Microform 52229:171-52229:200.

NRC, 1989c. U.S. Nuclear Regulatory Commission (Shipers and Harlan), “Background Information for the Development of a Low-Level Waste Performance Assessment Methodology, Assessment of Relative Significance of Migration and Exposure Pathways,” NUREG/CR-5453, Vol. 2, Public Legacy Library Accession No. 9001100237, Microform 2231:340-52232:037.

NRC, 1989d. U.S. Nuclear Regulatory Commission (Hunter, R.L. and Mann, C.J.), “Techniques for Determining Probabilities of Events and Processes Affecting Performance of Geologic Repositories,” NUREG/CR-3964, Vol. 1, June 1989, Public Legacy Library Accession No. 8907050519, Microform: 50354:071-50354:259.

NRC, 1989e. U.S. Nuclear Regulatory Commission, “Environmental Monitoring of Low-Level Radioactive Waste Disposal Facility,” NUREG-1388, December 1989, ADAMS Accession No. ML053010320.

NRC, 1990a. U.S. Nuclear Regulatory Commission, "Uncertainties Associated with Performance Assessment of High-Level Radioactive Waste Repositories,” NUREG/CR-5211, (SAND88-2703), Washington, D.C. 1990. https://ntrlr3.ntis.gov/view.php?pid=NTIS:NUREGCR5211

NRC, 1990b. U.S. Nuclear Regulatory Commission, "Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure,” NUREG/CR-1667, (SAND80-1429), Washington, DC, April 1990. https://ntrlr3.ntis.gov/view.php?pid=NTIS:NUREGCR1667

NRC, 1991a. U.S. Nuclear Regulatory Commission, “Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility,” NUREG-1199, Rev. 2, Washington, DC, January 1991, ADAMS Accession No. ML022550605.

NRC, 1991b. U.S. Nuclear Regulatory Commission, Technical Position on Waste Form, Rev. 1, Washington, DC, January 18, 1991, ADAMS Accession No. ML033630746.

NRC, 1991c. U.S. Nuclear Regulatory Commission, “Quality Assurance Guidance for a Low-Level Radioactive Waste Disposal Facility,” Office of Nuclear Material Safety and

Safeguards, Division of Low-Level Waste Management and Decommissioning, NUREG-1293, Rev. 1, April, 1991, ADAMS Accession No. ML11242A180.

NRC, 1992. U.S. Nuclear Regulatory Commission, "Residual Radioactive Contamination from Decommissioning, Technical Basis for Translating Contamination Levels for Annual Total Effective Dose Equivalent," NUREG/CR-5512 (PNL-7994), Washington, DC, October 1992, ADAMS Accession No. ML052220317.

NRC, 1993a. U.S. Nuclear Regulatory Commission, "Evaluation of a Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities: Evaluation of Modeling Approaches," NUREG/CR-5927, Vol. 1, (SAND91-2802), Washington, DC, August 1993, ADAMS Accession No. ML11126A295.

NRC, 1993b. U.S. Nuclear Regulatory Commission (Wierenga, P.J., M.H. Young, G.W. Gee, C.T. Kincaid, R.G. Hills, T.J. Nicholson, and R.E. Cady), "Soil Characterization Methods for Unsaturated Low-Level Waste Sites," NUREG/CR-5988, National Technical Information Service, Springfield, VA, February 1993, Public Legacy Library Accession No. 9303120106, Microform: 74236:120-74236:269.

NRC, 1994. U.S. Nuclear Regulatory Commission, "Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility," NUREG-1200, Rev. 3, Washington, DC, April 1994, ADAMS Accession No. ML061370484.

NRC, 1995a. U.S. Nuclear Regulatory Commission, "Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities: Final Policy Statement," *Federal Register,* Vol. 60, No. 158, pp. 42622– 42630, August 16, 1995.

NRC, 1995b. U.S. Nuclear Regulatory Commission, "Final Branch Technical Position on Concentration Averaging and Encapsulation, Revision in Part to Waste Classification Technical Position," Washington, DC, January 17, 1995, ADAMS Accession No. ML033630732.

NRC, 1995c. U.S. Nuclear Regulatory Commission, "Review of Scenario Selection Approaches for Performance Assessment of High-Level Waste Repositories and Related Issues," NUREG/CR-6351, (CNWRA 94-002), Washington, DC, August 1995, ADAMS Accession No. ML040080567.

NRC, 1995d. U.S. Nuclear Regulatory Commission, "Reassessment Of NRC's Dollar Per Person-Rem Conversion Factor Policy," NUREG-1530, Washington, DC, August 1995, Public Legacy Library Accession No. 9601290154, Microform 86877:334-86877:356. http://pbadupws.nrc.gov/docs/ML0634/ML063470485.pdf

NRC, 1995e. U.S. Nuclear Regulatory Commission (MacKinnon, R.J., T.M. Sullivan, S.A. Simonson, and C.J. Suen), "BLT-EC (Breach, Leach, Transport, and Equilibrium Chemistry), a Finite-Element Model for Assessing the Release of Radionuclides From Low-Level Waste Disposal Units Background, Theory, and Model Description," NUREG/CR-6305, Brookhaven National Laboratory, Upton, NY, 1995, Public Legacy Library Accession No. 9509200030, Microform 85540:001-85540:155.

NRC, 1996. U.S. Nuclear Regulatory Commission, “Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program,” NUREG-1563, Washington, DC, November 1996, ADAMS Accession No. ML033500190.

NRC, 1998. U.S. Nuclear Regulatory Commission, “Instructions for Completing NRC’s Uniform Low-Level Radioactive Waste Manifest,” NUREG/BR-0204, Revision 2, July 1998.

NRC, 1999a. U.S. Nuclear Regulatory Commission, “Regulatory Perspectives on Model Validation in High-Level Radioactive Waste Management Programs: A Joint NRC/SKI White Paper,” NUREG-1636, March 1999, ADAMS Accession No. ML012260054.

NRC, 1999b. U.S. Nuclear Regulatory Commission (Young, M.H., P.J. Wierenga, A.W. Warrick, L.L. Hofmann, S.A. Musil, M. Yao, C.J. Mai, Z. Zou, and B.R. Scanlon), “Results of Field Studies at the Maricopa Environmental Monitoring Site, Arizona,” NUREG/CR-5694, National Technical Information Service, Springfield, VA, June 1999, ADAMS Accession No. ML070590169.

NRC, 1999c. U.S. Nuclear Regulatory Commission (Young, M.H., A.W. Warrick, P.J. Wierenga, L.L. Hofmann, and S.A. Musil), “Comparing Monitoring Strategies at the Maricopa Environmental Monitoring Site, Arizona,” NUREG/CR-5698, National Technical Information Service, Springfield, VA, July 1999, ADAMS Accession No. ML062340324.

NRC, 1999d. U.S. Nuclear Regulatory Commission, “White Paper on Risk-Informed and Performance-Based Regulation,” SECY-98-144.

NRC, 2000a. U.S. Nuclear Regulatory Commission, “A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities: Recommendations of NRC’s Performance Assessment Working Group,” NUREG-1573, Washington, DC, October 2000, ADAMS Accession No. ML003770778.

NRC, 2000b. U.S. Nuclear Regulatory Commission (Robertson, D.E., C.W. Thomas, S.L. Pratt, E.A. Lepel, V.W. Thomas), “Low-Level Radioactive Waste Classification, Characterization, and Assessment: Waste Streams and Neutron-Activitated Metals,” NUREG/CR-6567, Washington, DC, August 2000, ADAMS Accession No. ML003752437.

NRC, 2000c. U.S. Nuclear Regulatory Commission, “Technical Report on a Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Methods,” SECY-00-0182, 2000.

NRC, 2001. U.S. Nuclear Regulatory Commission, “Integrated Safety Analysis Guidance Document,” NUREG-1513, Washington, DC, May 2001, ADAMS Accession No. ML031340285.

NRC, 2002a. U.S. Nuclear Regulatory Commission, “SRM–SECY–01–0148, Staff Requirements Memoranda, SECY–01–0148, Processes for Revision of 10 CFR Part 20 Regarding Adoption of ICRP Recommendations on Occupational Dose Limits and Dosimetric Models and Parameters,” April 12, 2002, ADAMS Accession No. ML021050104.

NRC, 2002b. U.S. Nuclear Regulatory Commission, “Design of Erosion Protection for Long-Term Stabilization,” NUREG-1623, Washington, DC, September 2002, ADAMS Accession No. ML052720285.

NRC, 2003a. U.S. Nuclear Regulatory Commission (Robertson, D.E., D.A. Cataldo, B.A. Napier, K.M. Krupka, and L.B. Sasser), “Literature Review and Assessment of Plant and Animal Transfer Factors Used in Performance Assessment Modeling,” NUREG/CR-6825, Pacific Northwest National Laboratory, Richland, WA, August 2003, ADAMS Accession No. ML032680646.

NRC, 2003b. U.S. Nuclear Regulatory Commission, "A Comprehensive Strategy of Hydrogeologic Modeling and Uncertainty Analysis for Nuclear Facilities and Sites," NUREG/CR-6805, Washington, D.C. July 2003. https://ntrlr3.ntis.gov/view.php?pid=NTIS:NUREGCR6805

NRC, 2003c. U.S. Nuclear Regulatory Commission, “Yucca Mountain Review Plan,” NUREG-1804, Rev. 2 (Final Report), Washington, DC, July 31, 2003, ADAMS Accession No. ML032030389.

NRC, 2003d. U.S. Nuclear Regulatory Commission, “Environmental Review Guidance for Licensing Actions Associated with NMSS Programs, Final Report,” NUREG-1748, 2003.

NRC, 2004a. U.S. Nuclear Regulatory Commission, “Risk Analysis Baseline Report,” Washington, DC, April 2004, ADAMS Accession No. ML040560162.

NRC, 2004b. U.S. Nuclear Regulatory Commission, “Multi-Agency Radiological Laboratory Analytical Protocols Manual (MARLAP),” NUREG-1576, EPA 402-B-04-001A, NTIS PB2004-105421, U.S. Environmental Protection Agency, U.S. Department of Defense, U.S. Department of Energy, U.S. Department of Homeland Security, U.S. Nuclear Regulatory Commission, U.S. Food and Drug Administration, U.S. Geological Survey, and National Institute of Standards and Technology, July 2004, ADAMS Accession No. ML042310547, ML042310738, ML042320083.

NRC, 2004c. U.S. Nuclear Regulatory Commission, Nicholson, T.J., et al., eds., “Proceedings of the International Workshop on Uncertainty, Sensitivity, and Parameter Estimation for Multimedia Environmental Modeling,” NUREG/CP-0187, Washington, DC, 2004, ADAMS Accession No. ML043440445.

NRC, 2004d. U.S. Nuclear Regulatory Commission, “Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission,” NUREG/BR-0058, Rev. 4, September 2004.

NRC, 2006. U.S. Nuclear Regulatory Commission, “Consolidated Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Criteria—Final Report,” NUREG-1757, Vol. 1 and 2, Washington, DC, September 2006, ADAMS Accession No. ML063000243 and ML063000252.

NRC, 2007a. U.S. Nuclear Regulatory Commission, “NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations: Draft Final Report for Interim Use,” NUREG-1854, Washington, DC, August 2007, ADAMS Accession No. ML072360184.

NRC, 2007b. U.S. Nuclear Regulatory Commission, "History and Framework of Commercial Low-Level Waste Management in the United States," Advisory Committee on Nuclear Waste, Washington, DC, 2007, ADAMS Accession No. ML070600684.

NRC, 2007c. U.S. Nuclear Regulatory Commission (Napier, B.A., R.J. Fellows, and K.M. Krupka), "Soil-to-Plant Concentration Ratios for Assessing Food-Chain Pathways in Biosphere Models," NUREG/CR-6941, Pacific Northwest National Laboratory, Richland, WA, August 2007, ADAMS Accession No. ML072780220.

NRC, 2007d. U.S. Nuclear Regulatory Commission, "Consolidated Decommissioning Guidance; Notice of Revision to, Withdrawal of Portions of, and Process for Updating," *Federal Register*, Vol. 72, No. 158, pp. 46102–46103, August 16, 2007.

NRC, 2009. U.S. Nuclear Regulatory Commission, "Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME)," NUREG-1575, Supplement 1, EPA 402-R-09-001, DOE/HS-0004, U.S. Department of Defense, U.S. Department of Energy, U.S. Environmental Protection Agency, and U.S. Nuclear Regulatory Commission, January 2009, ADAMS Accession No. ML090260577.

NRC, 2010. U.S. Nuclear Regulatory Commission (Ebert, W.L.), "Radionuclide Release from Slag and Concrete Waste Materials Part 1: Conceptual Models of Leaching from Complex Materials and Laboratory Test Methods," NUREG/CR-7025, Argonne National Laboratory, Argonne, IL, December 2010, ADAMS Accession No. ML103550580.

NRC, 2011a. U.S. Nuclear Regulatory Commission (Nicholson, T.J. and H.D. Arlt), "Proceedings of the Workshop on Engineered Barrier Performance Related to Low-Level Radioactive Waste, Decommissioning, and Uranium Mill Tailings Facilities," NUREG/CP-0195, Washington, DC, August 2011, ADAMS Accession No. ML11238A056.

NRC, 2011b. U.S. Nuclear Regulatory Commission, " Engineered Covers for Waste Containment: Changes in Engineering Properties and Implications for Long-Term Performance Assessment," NUREG/CR-7028, Washington, D.C. December 2011, ADAMS Accession No. ML12005A111.

NRC, 2011c. U.S. Nuclear Regulatory Commission, "Technical Analysis Supporting Definition of Period of Performance for Low-level Waste Disposal," April 2011, ADAMS Accession No. ML111030586.

NRC, 2012a. "Draft Branch Technical Position on Concentration Averaging and Encapsulation, Rev. 1," May 2012, ADAMS Accession No. ML121170418.

NRC, 2012b. U.S. Nuclear Regulatory Commission, "Strategic Plan, Fiscal Years 2008-2013,"NUREG-1614, Vol. 5, Washington, DC, February 2012. http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1614/v5/sr1614v5.pdf

NRC, 2012c. U.S. Nuclear Regulatory Commission, "A Proposed Risk Management Regulatory Framework," NUREG-2150, Washington, DC, April 2012.

NRC, 2013. U.S. Nuclear Regulatory Commission, “Technical Assistance to Agreement States,” Management Directive 5.7, DT-13-07, March 28, 2013. http://nrc-stp.ornl.gov/procedures/md0507.pdf

NYSDEC, 2008. New York State Department of Environmental Conservation, “West Valley History and Future,“ Report from the Commissioner’s Policy Office, April 2008.

Onishi, 2008. Onishi, Y., “Surface Water Transport of Radionuclides,” in *Radiological Risk Assessment and Environmental Analysis*, Chapter 4, J.E. Till and H.A. Grogan, eds., Oxford University Press, Oxford, UK, 2008.

Pelletier, 2008. Pelletier, J.D., *Quantitative Modeling of Earth Surface Processes*, Cambridge University Press, Cambridge, UK, 2008.

Penman, 1940. Penman, H.L., “Gas and Vapour Movements in Soil I. The Diffusion of Vapours through Porous Solids,” *Journal of Agricultural Science*, 30: 437–462, 1940.

Rockhold, 1999. Rockhold, M.L., “Parameterizing Flow and Transport Models for Field-Scale Applications in Heterogeneous, Unsaturated Soils,” in *Assessment of Non-Point Source Pollution in the Vadose Zone*, pp. 243–260, D.L. Corwin, K. Loague, and T.R. Ellsworth, eds., Geophysical Monograph Series 108, American Geophysical Union, Washington, DC, 1999.

Rodwell et al., 2003. Rodwell, W., S. Norris, W. Cool, M. Cuñado, L. Johnson, M. Mäntynen, W. Müller, P. Sellin, M. Snellman, J. Talandier, T. Vieno, and S. Vines, “A Thematic Network on Gas Issues in Safety Assessment of Deep Repositories for Radioactive Waste (GASNET): Final Report on the Treatment in Safety Assessments of Issues Arising from Gas Generation,” European Commission, Luxembourg, August 19, 2003.

Rubin, 2003. Rubin, Y., *Applied Stochastic Hydrogeology*, Oxford University Press, Oxford, UK, 2003.

Scanlon et al., 2000. Scanlon, B.R., J.P. Nicot, and J.M. Massmann, “Soil Gas Movement in Unsaturated Systems,” in *Handbook of Soil Science*, Chapter 8, M.E. Sumner, ed., CRC Press, Washington, DC, 2000.

Sheppard and Thibault, 1990. Sheppard, M.I., and D.H. Thibault, “Default Soil Solid/Liquid Partition Coefficients, K_d, for Four Major Soil Types: A Compendium,” *Health Physics*, 59: 471–482, 1990.

Shetrone, 2004. Shetrone, H.C., *The Mound Builders*, University of Alabama Press, reprint 2004.

Sorensen et al., 1999. Sorensen, J.N., G.E. Apostolakis, T.S. Kress, and D.A. Powers, “On the Role of Defense in Depth in Risk-Informed Regulation,” *Proceedings of PSA ’99, International Topical Meeting on Probabilistic Safety Assessment*, pp. 408-413, August 22 -26, 1999, American Nuclear Society: La Grange Park, Illinois.

SKB, 2006. Svensk Kärnbränslehantering (SKB), “Long-term Safety for KBS-3 Repositories at Forsmark and Laxemar – A First Evaluation,” Main report of the SR-Can project, SKB TR-06-09, 2006.

SKB, 2008. Svensk Kärnbränslehantering, "Project SFR 1 SAR-08: Update of priority of FEPs from Project SAFE," SKB Rapport R-08-12, ISSN 1402-3091, Stockholm, March 2008.
SSI, 1996. Swedish Radiation Protection Institute (SSI), “Development of a Reference Biospheres Methodology for Radioactive Waste Disposal, Final Report of the Reference Biospheres Working Group of the BIOMOVS II Study,” Technical Report No. 6, SSI, Stockholm, Sweden, September 1996.

Staven et al., 2003. Staven, L.H., K. Rhoads, B.A. Napier, and D.L. Strenge, “A Compendium of Transfer Factors for Agricultural and Animal Products,” PNNL-13421, Pacific Northwest National Laboratory, Richland, WA, 2003.

Stedinger and Cohen, 1986. Stedinger, J.R., and Cohen, T.A., “Flood frequency analysis with historical and paleoflood information,”Water Resources Research 22, 785-793.

Stutzman and Clifton, 1997. Stutzman, P.E., and J.R. Clifton, “Stone Exposure Test Wall at NIST,” in *Proceedings of Degradation of Natural Stone*, J.F. Labuz, ed., American Society of Civil Engineers Annual Meeting, Minneapolis, MN, 1997.

Sullivan, 2006. Sullivan, T.M., “DUSTMS-D: Disposal Unit Source Term — Multiple Species — Distributed Failure, Data Input Guide,” BNL-75554-2006, Brookhaven National Laboratory, Upton, NY, 2006.

Syvitski et al., 2011. Syvitski, J.P., et al., “CSDMS — A Modeling System to Aid Sedimentary Research,” *The Sedimentary Record*, 9(1): 4-9, 2011.

Todd, 1980. Todd, D.K., *Groundwater Hydrology,* John Wiley and Sons, New York, NY, 1980.

Troeh et al., 1982. Troeh, F.R., J.D. Jabro, and D. Kirkham, “Gaseous Diffusion Equations for Porous Materials,” *Geoderma*, 27: 239–253, 1982.

USGS, 1999. U.S. Geological Survey, “User’s Guide to PHREEQC (Version 2) — A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations,” *Water-Resources Investigations Report 99-4259*, U.S. Department of the Interior, USGS, Denver, CO, 1999.

Walter and Dubreuilh, 2007. Walter, G.R., and P. Dubreuilh, “Evaluation of Approaches to Simulate Engineered Cover Performance and Degradation,” Center for Nuclear Waste Regulatory Analyses, San Antonio, TX, 2007.

Wang et al., 1993. Wang, Y.Y., B.M. Biwer, and C. Yu, “A Compilation of Radionuclide Transfer Factors for the Plant, Meat, Milk, and Aquatic Food Pathways and the Suggested Default Values for the RESRAD Code,” Argonne National Laboratory, Argonne, IL, 1993.

Ward et al., 2009. Ward, A.L., et al., “Short- and Long-Term Fire Impacts on Hanford Barrier Performance,” *WM2009 Conference Proceedings*, March 1–9, 2009, Phoenix, AZ, 2009.

Waugh, 2004. Waugh, W.J., “Design, Performance, And Sustainability Of Engineered Covers For Uranium Mill Tailings, Proceedings of Long-term Performance Monitoring of Metals and Radionuclides in the Subsurface: Strategies, Tools, and Case Studies,” U.S. Environmental Protection Agency, U.S. Department of Energy, U.S. Geological Survey, Nuclear Regulatory Commission, April 21–22, 2004, Reston, VA, 2004.

Waugh, 2006. Waugh, W.J., “Sustainable Disposal Cell Covers: Legacy Management Practices, Improvements, and Long-Term Performance,” DOE LM/GJ1156-2006, US Department of Energy Office of Legacy Management, Grand Junction, CO, 2006.

Waugh and Richardson, 1997. Waugh, W.J. and Richardson, G.N., “Ecology, Design, and Long-Term Performance of Surface Barriers: Applications at a Uranium Mill Tailings Site,” in *Barrier Technologies for Environmental Management, Summary of a Workshop*, National Research Council, National Academy of Sciences, Washington, DC, 1997.

Wolery, 1992a. Wolery, T.J., “EQ3/6, a Software Package for Geochemical Modeling of Aqueous Systems: Package Overview and Installation Guide (Version 7.0),” UCRL-MA-110662, Part I, Lawrence Livermore National Laboratory, Livermore, CA, 1992.

Wolery, 1992b. Wolery, T.J., “EQ3NR, a Computer Program for Geochemical Aqueous Speciation-Solubility Calculations: Theoretical Manual, User’s Guide, and Related Documentation (Version 7.0),” UCRL-MA-110662, Part III, Lawrence Livermore National Laboratory, Livermore, CA, 1992.

Wolery and Daveler, 1992. Wolery, T.J., and S.A. Daveler, “EQ6, a Computer Code for Reaction-Path Modeling of Aqueous Geochemical Systems: Theoretical Manual, User’s Guide, and Related Documentation (Version 7.0),” UCRL-MA-110662, Part IV, Lawrence Livermore National Laboratory, Livermore, CA, 1992.

Yu et al., 1993. Yu, C., C. Loureiro, J.J. Cheng, L.G. Jones, Y.Y. Wang, Y.P. Chia, and E. Faillace, “Data Collection Handbook to Support Modeling Impacts of Radioactive Material in Soil,” Argonne National Laboratory, Argonne, IL, 1993.

Yu et al., 2001. Yu, C., A.J. Zielen, J.-J. Cheng, D.J. LePoire, E. Gnanapragasam, S. Kamboj, J. Arnish, A. Wallo, W.A. Williams, and H. Peterson, “User’s Manual for RESRAD Version 6,” ANL/EAD-4, Argonne National Laboratory, Argonne, IL, July 2001.

13.0 GLOSSARY

Alternative conceptual model: An additional and different model on how the system might work that is consistent with available supporting information. For example, a scenario may have a matrix flow conceptual model and an alternative fracture flow conceptual model; the model outputs from each may yield significantly different results.

Alternative scenario: In addition to the central scenario, possible future evolution of the disposal site. Alternative scenarios may include disruptive events if those FEPs are relevant at a particular site.

Analysis timeframe: The timeframe over which a licensee should assess the projected performance of the disposal facility factoring in the characteristics of the waste, engineered barriers, disposal site, and associated uncertainties. The analysis timeframe is divided into two phases: a compliance period and a performance period.

Assessment Context: The assessment context provides a framework for performance assessment and covers the following key aspects: purpose; regulatory framework; assessment end-points; assessment philosophy; disposal system (or facility) characteristics; and timeframes.

Buffer zone: Portion of the disposal site that is controlled by the licensee and that lays under the disposal units and between the disposal units and the boundary of the site.

Central scenario: The scenario that the licensee can best support as to the expected future dynamic evolution of the disposal site. As a result of the site selection process for low-level waste disposal, the central scenario generally will not include disruptive events.

Code: A set of software commands used to solve mathematical equations representing phenomena of the conceptual model.

Compliance period: The period of time over which a licensee must demonstrate with reasonable assurance that the disposal facility will meet the performance objectives found in 10 CFR 61.41(a), 10 CFR 61.42(a), and 10 CFR 61.44. A quantitative assessment should be performed. The compliance period is defined by 10 CFR 61.2 to be the time out to 1,000 years after closure of the disposal facility.

Computational model: See *Numerical model.*

Conceptual model: A well-defined, connected sequence of phenomena describing the behavior of the system of concern.

Critical group*:* A group of individuals reasonably expected to receive the greatest exposure to releases over time, given the circumstances under which the analysis would be carried out. The average member of the critical group is that individual who is assumed to represent the most likely exposure situation, based on cautious but reasonable exposure assumptions and parameter values.

Defense-in-depth: The use of multiple independent and redundant layers of defense such that no single layer, no matter how robust, is exclusively relied upon. Defense-in-depth for a land disposal facility includes, but is not limited to, the use of siting, waste forms and radionuclide content, engineered features, and natural geologic features of the disposal site.

Degradation: A process of gradual reduction in the capability of materials used in the construction of low-level waste disposal facilities to limit water infiltration and the release of radionuclides; the decline of an engineered barrier following the service life, when important characteristics of an engineered barrier progress from an expected design value to the degraded condition.

Degraded barrier: An engineered barrier that has fully undergone the process of degradation resulting in reduced material and performance characteristics: a degraded barrier could still perform a function based on the properties of the remaining durable constituent materials.

Deterministic analysis: An analysis using a single set of values for key assumptions or parameters to calculate a single value of model output.

Disposal: Placement of waste in a facility designed to isolate waste from the accessible environment without an intention to retrieve the waste.

Disposal site: That portion of a land disposal facility which is used for disposal of waste. It consists of disposal units and a buffer zone.

Disposal unit: A discrete portion of the disposal site into which waste is placed for disposal. For near-surface disposal the unit is usually a trench.

Distribution coefficient (K_d): An empirical constant employed in mathematical expressions representing sorption isotherms that relate the mass of solute on the solid phase to the concentration of solute in solution as a function of temperature and pressure. The distribution coefficient (K_d) represents an empirical constant for a linear sorption isotherm, the validity of which requires that the reactions that cause the partitioning are fast and reversible (e.g., chemical equilibrium is achieved) and the sorption isotherm is linear.

Dose: Generically refers to radiation dose, absorbed dose, dose equivalent, effective dose equivalent, committed dose equivalent, committed effective dose equivalent, or total effective dose equivalent.

Dosimetry: The process or method of measuring the dosage of ionizing radiation.

Engineered barrier: A man-made feature that is intended to improve the land disposal facility's ability to meet the performance objectives in Subpart C. Examples of engineered barriers include intruder barrier, resistive cover, evapotranspiration or water balance cover, and clay cap.

Exposure pathway: The route by which radioactivity travels through the environment to produce radiation exposure to a person or group.

Exposure scenario: See *Receptor scenario.*

Event: A qualitative or quantitative phenomenon or change that has the potential to affect the performance of the disposal system and that occurs during an interval that is short compared to the analyses timeframe. Examples of events that cause relative rapid change are earthquakes, floods, storms, well drilling, and excavation.

Feature: An object, structure, or characteristic that has a potential to affect the performance of the disposal system. Examples include rocks within an erosion layer of an engineered cover or a drainage layer of an engineered cover.

FEP: Feature, event, or process that has a potential to affect the performance of the disposal system.

FEP categorization: The process of organizing individual FEPs into categories of similar properties to facilitate FEP screening. For example, FEPs related to natural, human, or waste phenomena may be grouped into separate categories.

FEP screening: The process of using regulatory, probability, and consequence criteria to eliminate FEPs from further consideration that will not significantly impact the performance of the disposal system or are otherwise excluded by regulation.

Hazard: A feature, event, or process that is capable of causing harm. In waste disposal, the radiological inventory represents a hazard but if contained does not present risk to the public.

Inadvertent intruder: Any person who might occupy the disposal site after closure and engage in normal activities, such as agriculture, dwelling construction, resource exploration or exploitation (e.g., well drilling) or other reasonably foreseeable pursuits that might unknowingly expose the person to radiation from the waste.

Institutional controls: Measures to control access to a site and minimize disturbances to engineered measures established by the licensee to control the residual radioactivity. Institutional controls include administrative mechanisms (e.g., land use restrictions) and may include, but are not limited to, physical controls (e.g., signs, markers, landscaping, and fences).

Intruder assessment: An analysis that (1) assumes an inadvertent intruder occupies the site or contacts the waste and engages in normal activities or other reasonably foreseeable pursuits that might unknowingly expose the person to radiation from the waste; (2) examines the capabilities of intruder barriers to inhibit an inadvertent intruder's contact with the waste or to limit the inadvertent intruder's exposure to radiation; and (3) estimates an inadvertent intruder's potential annual dose, considering associated uncertainties. Intruder assessments are generally constrained to a limited set of receptor scenarios to avoid excessive speculation about future human behavior. An intruder assessment is used to demonstrate compliance with 10 CFR 61.42(a) and 10 CFR 61.42(b).

Intruder scenario: See *Receptor scenario.*

Land disposal facility: The land, building, and structures, and equipment which are intended to be used for the disposal of radioactive wastes.

Licensee: A person possessing a license to dispose of waste in a land disposal facility. In this document the term "licensee" is meant to include both persons possessing a 10 CFR Part 61 license as well as applicants who are applying to obtain a 10 CFR Part 61 license.

Long-lived waste: Waste containing radionuclides (1) where more than 10 percent of the initial activity of a radionuclide remains after 10,000 years (e.g., long-lived parent), (2) where the peak activity from progeny occurs after 10,000 years (e.g., long-lived parent – short-lived progeny), or (3) where more than 10 percent of the peak activity of a radionuclide (including progeny) within 10,000 years remains after 10,000 years (e.g., short-lived parent – long-lived progeny).

Low-level (radioactive) waste (LLW): Items that have become contaminated with radioactive material or have become radioactive through exposure to radiation. The radioactivity in these wastes can range from just above natural background levels to much higher levels, such as seen in parts from inside the reactor vessel in a nuclear power plant. Low-level radioactive waste is defined by what it is not, so that an understanding of the definitions of high-level radioactive waste, spent nuclear fuel, transuranic waste, byproduct material, and naturally occurring radioactive material is necessary to determine whether a subject waste is low-level waste.

Mathematical model: A representation of a conceptual model in mathematical terms (i.e., a governing equation or set of equations intended to represent important processes). Mathematical models can be solved analytically or numerically.

Member of the public: An individual in a controlled or unrestricted area. However, an individual is not a member of the public during any period in which the individual receives an occupational dose.

Model: A conceptual or mathematical representation of a system used to project future performance.

Model abstraction: The process of abstracting a conceptual model representing a dynamic site in the physical world into a mathematical model governed by equations that is implemented within a numerical model.

Model integration: The connection of models, submodels, and abstractions at the level of detail necessary to represent the conceptual model. For example, a model simulating precipitation may be integrated with models of infiltration and erosion.

Model simplification: The process of simplifying a complex numerical model into a reduced numerical model while still maintaining the validity of the simulation results.

Model support: The technical basis that demonstrates the validity and appropriateness of the results of the numerical model, and by extension provides support for the conceptual model. The basis may include comparisons made with outputs of models (e.g., detailed process-level models) and/or empirical observations (e.g., laboratory testing, field investigations, and natural analogs).

Model uncertainty: The uncertainty in the conceptualization of the system, the uncertainty in its mathematical representation, and the uncertainty in the solution of the mathematical representation.

Monitoring: Observing and making measurements to provide data to evaluate the performance and characteristics of the disposal site.

Near-surface disposal facility: A land disposal facility in which radioactive waste is disposed of in or within the upper 30 meters of the earth's surface.

Numerical model: A model to solve the equations of the mathematical model using codes or modeling software. The results of the simulations can represent, for example, potential radiological exposures and their associated uncertainties.

Parameter uncertainty: Uncertainty associated with the input to the numerical model being used in the analysis including uncertainty in the actual values and the statistical and spatial distributions of data use to infer model parameters. Parameter uncertainty is highly dependent on the quality of the data.

Pathway: Route or means of release of contaminants from a disposal facility, transport of contaminants in the environment, or exposure of humans.

Performance assessment: An analysis that (1) identifies the features, events, and processes that might affect the disposal system; (2) examines the effects of these features, events, and processes on the performance of the disposal system; and (3) estimates the annual dose to any member of the public caused by all significant features, events, and processes. A performance assessment is used to demonstrate compliance with 10 CFR 61.41(a) and 10 CFR 61.41(b).

Performance period: The period of time over which a licensee evaluates the ability of the disposal system to contain long-lived waste and demonstrates that releases are minimized to the extent reasonably achievable. The performance period begins at the end of the protective assurance period and extends as long as necessary to demonstrate that the metric of the performance period can be met.

Performance period analyses*:* Analyses for certain types of waste for the timeframe after the compliance period, which assess how the disposal facility and site characteristics minimize the potential long-term impacts. Performance period analyses are required if the disposal facility is accepting long-lived waste that has disposal site-averaged concentrations of long-lived radionuclides greater than the values provided in Table A of 10 CFR 61.13(e). Performance period analyses may be conservative screening analyses or a probabilistic risk assessment.

Phenomenon: Either a process or an event. Typically, a phenomenon acts upon a feature.

Probabilistic analysis: Refers to computer codes or analyses that use a sampling method to select parameter values from a distribution. Results of the calculations are also in the form of a distribution of values or time series of different values.

Process: A qualitative or quantitative phenomenon or change that has the potential to affect the performance of the disposal system and that occurs <u>during all or a significant part</u> of the analyses timeframe. Examples of processes that cause relative gradual change are radionuclide transport, differential settlement, leaching, and erosion.

Protective assurance period: The period from the end of the compliance period through 10,000 years following closure of the site.

Qualified specialist: A person, by reason of training or experience, who possesses expertise in a particular field or scientific study (e.g., geomorphologist, seismologist, or chemist).

Radionuclide inventory: The isotopic distribution of radioactive materials by waste class, wasteform, and waste container disposed of in the facility and potentially available for release to the environment.

Receptor: The exposed individual relative to the exposure pathway considered.

***Receptor scenario**:* A type of scenario that describes the FEPs associated with people becoming exposed to radiation.

Reviewer: This document uses the term “reviewer” to include NRC staff reviewers as well as Agreement State reviewers.

Risk: The combined answer to the three questions that consider (1) what can go wrong, (2) how likely it is, and (3) what the consequences might be. In the context of radioactive waste disposal risk refers to probability-weighted radiological doses.

Safety assessment: A systematic analysis of the ability of the site and design to provide the safety functions and meet technical requirements.

Safety case: A collection of information that demonstrates the assessment of the safety of a waste disposal facility. This includes technical analyses, such as the performance assessment and intruder assessment, but also includes information on defense-in-depth and supporting evidence and reasoning on the strength and reliability of the technical analyses and the assumptions made therein. The safety case also includes descriptions of the safety relevant aspects of the site, the design of the facility, and the managerial control measures and regulatory controls.

Safety function: Defined qualitatively as a function through which a component of the disposal system contributes to safety and achieves its safety objective throughout the analyses timeframe.

Scenario: A future evolution of the disposal site resulting from a subset of FEPs.

Scenario development: The process of incorporating a site's current and future features, events, processes, and their interactions into a scenario. Frequently, a top-down or bottom-up approach is used, or a mixture of the two.

Scenario uncertainty: Uncertainty about the future of the site due to the inherent lack of knowledge about how the site will evolve in time.

Sensitivity analysis: An examination of how the behavior of a system varies with change, usually in the values of the governing parameters. An analysis to investigate the dependencies of the result of the assessment on the alternative input elements (i.e. data, assumption, etc.).

Site characterization: Studies that enable the licensee to sufficiently describe the conditions of the site to evaluate the acceptability of the decommissioning plan.

Site closure and stabilization: Those actions that are taken upon completion of operations that prepare the disposal site for custodial care and that assure that the disposal site will remain stable and will not need ongoing active maintenance.

Site stability analyses: Analyses considering the potential effects of erosion, flooding, seismicity, and other disruptive processes and events on the ability of the disposal facility to meet the performance objectives. In addition, such analyses consider the potential effects of degradation of mechanical properties of containers or other stabilizing man-made features. Stability analyses may be design-based or model-based and may or may not be based on risk considerations.

Solubility limit: The maximum amount of a radionuclide (solute) that can be dissolved per unit of liquid (solvent) under specified conditions (e.g., temperature, pH).

Source term: A conceptual representation of the radionuclide inventory in a disposal site. The quantity of radionuclides expected to be released over time out of a clearly identified boundary (such as the wasteform, container, disposal unit, or facility).

Stability: A term that refers to the ability of the waste and the disposal site to maintain their physical characteristics so that once waste is emplaced, backfilled, and covered, water access to the waste and release of radioactivity is minimized.

Surveillance: Observation of the disposal site for purposes of visual detection of need for maintenance, custodial care, evidence of intrusion, and compliance with other license and regulatory requirements.

System description: A description of the characteristics and interactions, including features and phenomena, of the disposal site and surrounding area to ensure information used to develop the technical analyses and describing the overall disposal system performance have been adequately described.

Technical analyses: Analyses associated with the performance assessment, the intruder assessment, the stability evaluation, and the performance period needed to demonstrate compliance with the Subpart C performance objectives.

Total effective dose equivalent (TEDE): The sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (CEDE) (for internal exposures) (see 10 CFR 20.1003).

Upscaling: The modification of data for use at a different scale. Most commonly upscaling transforms data from fine-scale observations for use at a much coarser scale.

Uncertainty analysis: A method of formally assessing, reducing or managing, and documenting the inherent uncertainties of a system. The uncertainties include model uncertainty (which spans conceptual model uncertainty and mathematical model uncertainty), uncertainty about the future of the site, and parameter uncertainty (i.e., uncertainty in values used in the numerical model).

Validation (model): The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

Verification (software): Comparison of the numerical solution generated by the computational model with one or more analytical solutions or with other numerical solutions. Verification of the code ensures that the computer program accurately solves the equations that constitute the mathematical model. Verification of the governing equation demonstrates that it accurately describes the physical processes that occur.

Waste acceptance criteria: Administrative limits, required by 10 CFR Part 61.58 that provide reasonable assurance of compliance with the performance objectives of Subpart C. The criteria include allowable activities and concentrations of specific radionuclides, acceptable wasteform characteristics and container specifications, and restrictions or prohibitions on waste, materials, or containers that might affect the facility's ability to meet the performance objectives in Subpart C.

Waste incidental to reprocessing (WIR): Wastes that are incidental to the reprocessing of nuclear fuel that can be managed as LLW.

Waste stream: The origin of a low-level waste type or combination of waste types with a particular radionuclide content and distribution independent of its physical characteristics.

Waste type: Radioactive materials such as cloth, wood, plastic, glass, or metal, or other substances obtained from radioactive waste treatment systems, industrial processes, or research experiments. Some examples of waste types are dry solids, dry active waste, ion exchange resins, sorbed liquids, filter cartridges, and activated metals.

Wasteform: Radioactive waste in its physical and chemical form including any stabilizing or encapsulating material within which it is incorporated.

APPENDIX A
CHANGES TO 10 CFR PART 61 MADE IN 2015 RULEMAKING

Table A-1 Comparison Table of Current and Proposed 10 CFR Part 61 Regulations

	Protection of the general population from releases of radioactivity (10 CFR 61.41)	**Protection of individual from inadvertent intrusion (10 CFR 61.42)**	**Stability of the disposal site after closure Long-term analyses (10 CFR 61.44)**	**Defense-in-Depth**
Current 10 CFR Part 61 regulations	- Pathway analysis - Undefined period of performance - 0.25 mSv (25 mrem) annual whole body dose limit for the protection of the general population - ALARA concept	- Comply with 10 CFR 61.55 - Provide adequate barriers to inadvertent intrusion - Undefined period of performance - No annual dose limit	Analyses of active natural processes that demonstrate that there will not be a need for ongoing active maintenance of the disposal site following closure.	Implicit in Subpart D technical requirements.
Proposed 10 CFR Part 61 regulations	**Within 1,000 Years Following Closure of Disposal Facility (Compliance Period)**			
	- Performance assessment that estimates peak annual dose that occurs within 1,000 years following closure - 0.25 mSv (25 mrem) annual dose limit for the protection of the general population from the releases of radioactivity that occurs within 1,000 years - ALARA concept	- Comply with LLW acceptance criteria - Provide adequate barriers to inadvertent intrusion - Intruder assessment that estimates peak annual dose that occurs within 1,000 years following closure of disposal facility - 5 mSv (500 mrem) annual dose limit	Analyses of active natural processes that demonstrate that long-term stability of the site can be ensured and that there will not be a need for ongoing active maintenance of the disposal site following closure.	Analyses that demonstrate the proposed disposal system includes defense-in-depth protections.

Table A-1 Comparison Table of Current and Proposed 10 CFR Part 61 Regulations

	Protection of the general population from releases of radioactivity (10 CFR 61.41)	Protection of individual from inadvertent intrusion (10 CFR 61.42)	Stability of the disposal site after closure Long-term analyses (10 CFR 61.44)	Defense-in-Depth
	Between 1,000 and 10,000 Years Following Closure of Disposal Facility (Protective Assurance Period)			
	- Performance assessment that estimates peak annual dose that occurs between 1,000 and 10,000 years following closure of disposal facility - Annual dose shall be below 5 mSv (500 mrem) or a level that is reasonably achievable based on technological and economic considerations for the protection of the general population from releases of radioactivity that may occur between 1,000 and 10,000 years following closure	- Intruder assessment that estimates peak annual dose that occurs between 1,000 and 10,000 years following closure of disposal facility - Annual dose shall be below 5 mSv (500 mrem) or a level that is reasonably achievable based on technological and economic considerations for the protection of the inadvertent intruders from exposures that may occur between 1,000 and 10,000 years following closure	Analyses of active natural processes that demonstrate that long-term stability of the site can be ensured and that there will not be a need for ongoing active maintenance of the disposal site following closure.	Analyses that demonstrate the proposed disposal system includes defense-in-depth protections.
	After 10,000 Years Following Closure of Disposal Facility (Performance Period)			
	- Analyses for 10,000 or more years following closure of disposal facility that demonstrates releases will be	- Analyses for 10,000 or more years following closure of disposal facility that demonstrates exposures will be		Analyses that demonstrate the proposed disposal system includes defense-in-depth protections.

Table A-1 Comparison Table of Current and Proposed 10 CFR Part 61 Regulations

	Protection of the general population from releases of radioactivity (10 CFR 61.41)	**Protection of individual from inadvertent intrusion (10 CFR 61.42)**	**Stability of the disposal site after closure Long-term analyses (10 CFR 61.44)**	**Defense-in-Depth**
	minimized to the extent reasonably achievable for the protection of the general population - Analyses only apply for disposal sites containing long-lived radionuclides exceeding concentrations listed in table A of 10 CFR 61.13(e), or if necessitated by site-specific conditions - Analyses that demonstrate how the facility has been designed to limit long-term releases.	minimized to the extent reasonably achievable for the protection of inadvertent intruders - Analyses only apply for disposal sites containing long-lived radionuclides exceeding concentrations listed in table A of 10 CFR 61.13(e), or if necessitated by site-specific conditions - Analyses that demonstrate how the facility has been designed to limit long-term exposures to an inadvertent intruder.		

APPENDIX B
HAZARD MAPS

The NRC staff created hazard maps related to the features and phenomena of the 10 CFR 61.50 criteria. The hazard maps presented in this appendix provide an illustration of features, events, and processes (FEPs) related to 10 CFR 61.50 site suitability criteria. The maps cannot be displayed in this document at sufficient size to be used to determine if any specific location would be impacted by one of these phenomena. The figures provide an illustration of potentially impacted areas.

The figures should not be used by regulators to prohibit disposal because the resolution of the maps and the precision and accuracy of the techniques used to generate them may not be sufficient for site-specific evaluations. However, regulators should use the maps to determine when greater review effort and more technical basis should be expected for the licensee's site-specific evaluation. In addition, the data used to produce these maps could be used, via Geographic Information System (GIS) software, to perform screening-level analyses of the FEPs.

<u>Preparation of the hazard maps:</u>

ArcGIS was used to process the data from the data sources and produce all of the maps. ERDAS Imagine was used to process image data used for the groundwater depth (B-4) and erosion (B-8) maps.

Figure B-1 – The source is elevation data compiled from various sources and provided by Environmental Systems Research Institute (ESRI). The NRC staff created an indicator plot for areas less than 5 m above the current sea level using data from ESRI (2008b).

Figure B-2 – Figure is based on wetlands land use classes from USGS land use/land cover data (USGS, 2011).

Figure B-3 - Where available, one percent annual chance flood event risk zones (100-year floodplain) from the FEMA Digital Flood Insurance Rate Map Database (DFIRM) are shown (FEMA, 2012). When DFIRM data was not available, one percent annual chance flood event risk zones (100-year floodplain) from the FEMA National Flood Insurance Program Q3 Flood Data are shown (FEMA, 1998). When DFIRM or Q3 FEMA data were not available, the source is NRC staff calculations performed on data compiled and provided by ESRI (ESRI, 2008a; ESRI, 2008b). A slope model (a grid where each cell is assigned maximum slope between it and the neighboring cells) was created from a digital elevation model (DEM) of the continental US. From the slope model, a flow direction grid was generated using the direction of maximum slope out of the cell. From the flow direction grid, a flow accumulation grid was generated based on how many cells lay upstream of the grid cell. Cells with a very low slope that accumulated flow over a certain threshold were displayed as black (prone to flooding), all others were white. On top of this image a hydrology layer was added that showed ponds, lakes, reservoirs, and large rivers as black.

Figure B-5 – The source is hydrology data compiled from various sources and provided by ESRI. The figure is based on the categories provided in the referenced data sources. There could be other data categories not in the ESRI data source that might be areas of previous flooding (ESRI, 2008a; ESRI, 2008b).

Figure B-6 through B-9 - The data were available for download from the websites listed in the references cited on the figure caption. Thirty five tiles of data that covered the continental U.S. were used. Each tile of data contained files representing the extent of glaciation at various times during the quaternary. There were four general time periods covered in most cases: the Younger Dryas, the Late Weichselian (Wisconsinian), the Early-Middle Weichselian, and the maximum limit of Pleistocene glaciation. For some tiles there were separate files for various features: ice sheets, mountain glaciers, and basin glaciers. Sometimes they were all combined into one file with a field in the attribute table which signified which type of feature it was. Sometimes there were separate data files for the work of from more than one author. Not all authors studied the entire continental U.S. The files representing like datasets were merged for all of the tiles and those files were clipped to the boundary of the continental U.S. plus Great Lakes. Areas in each file that represent ice covered areas for that particular time stamp are displayed as black on the map. By stacking all of the files from various authors and features on top of each other in the map, the maximum extent of glaciation for the period covered by these files is represented in the figure.

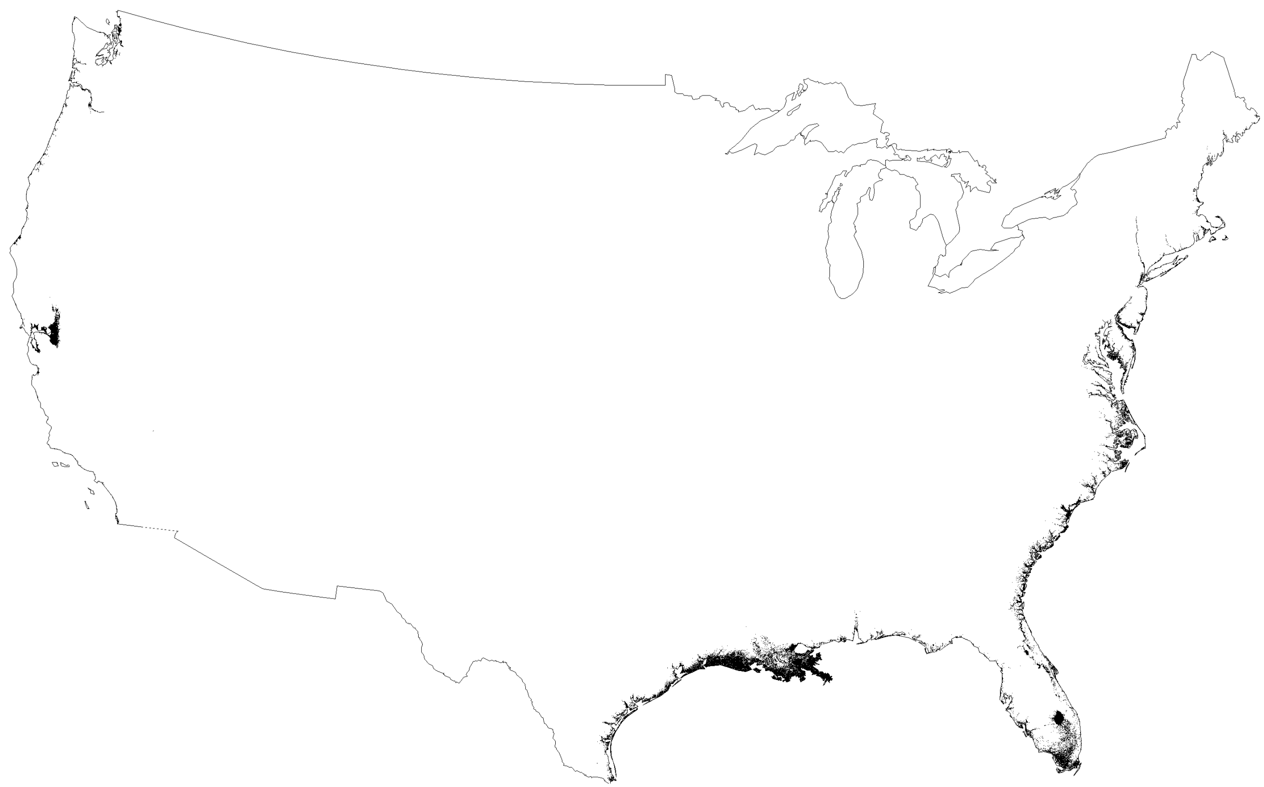

Figure B-1: Approximate area of land that might flood if mean sea level rose by 5 m. Proposed sites located near these areas may require additional analysis and evaluation (ESRI, 2008b)

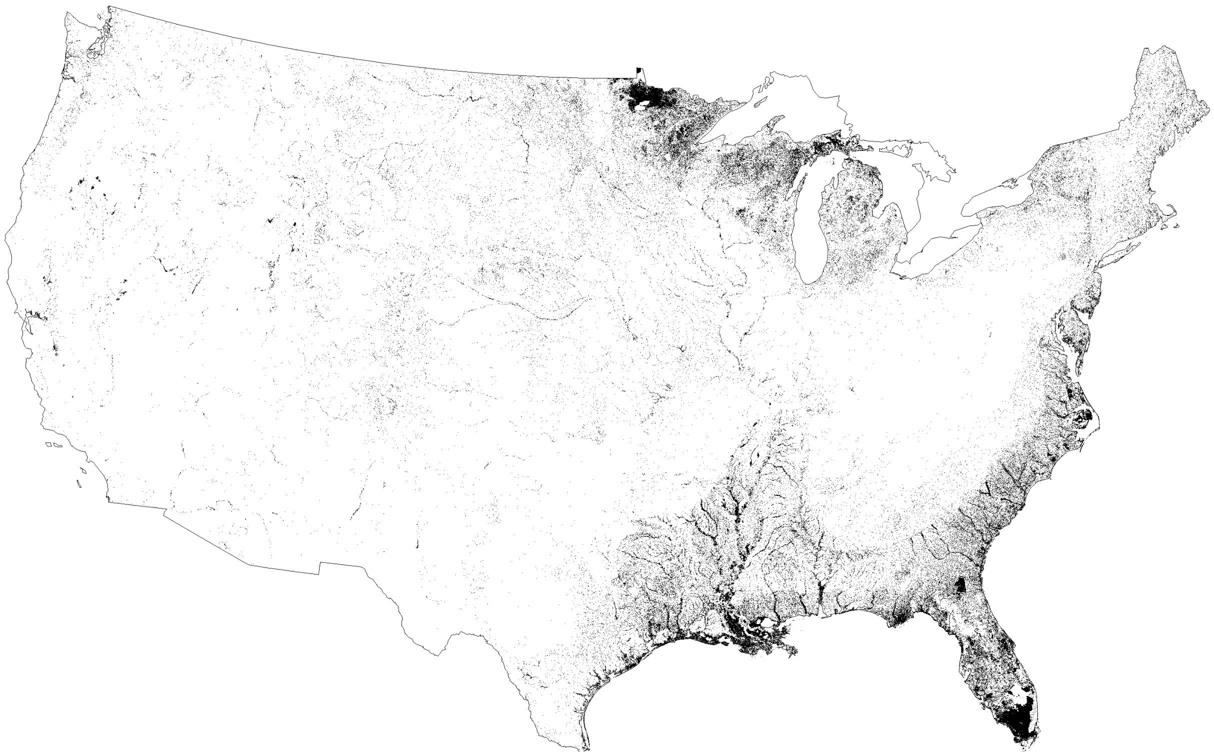

Figure B-2: Approximate area of current wetlands. Proposed sites located near these areas may require additional site characterization and analysis. Wetland areas in the future may change (USGS, 2011)

Figure B-3: Areas of potential flooding that may require additional site characterization and analysis (FEMA, 2012; FEMA, 1998; ESRI, 2008a; ESRI, 2008b)

Figure B-4: Approximate area of simulated current water tables shallower than 30 m. Proposed sites located in these areas may require additional site characterization and analysis. Future near-surface groundwater areas may change (Kreakie et al, 2012)

Figure B-5: Approximate areas that may have frequently flooded in the past (e.g., dry lake beds, salt flats, areas below sea level). Proposed sites located in these areas may require additional site characterization and analysis (ESRI, 2008a; ESRI, 2008b)

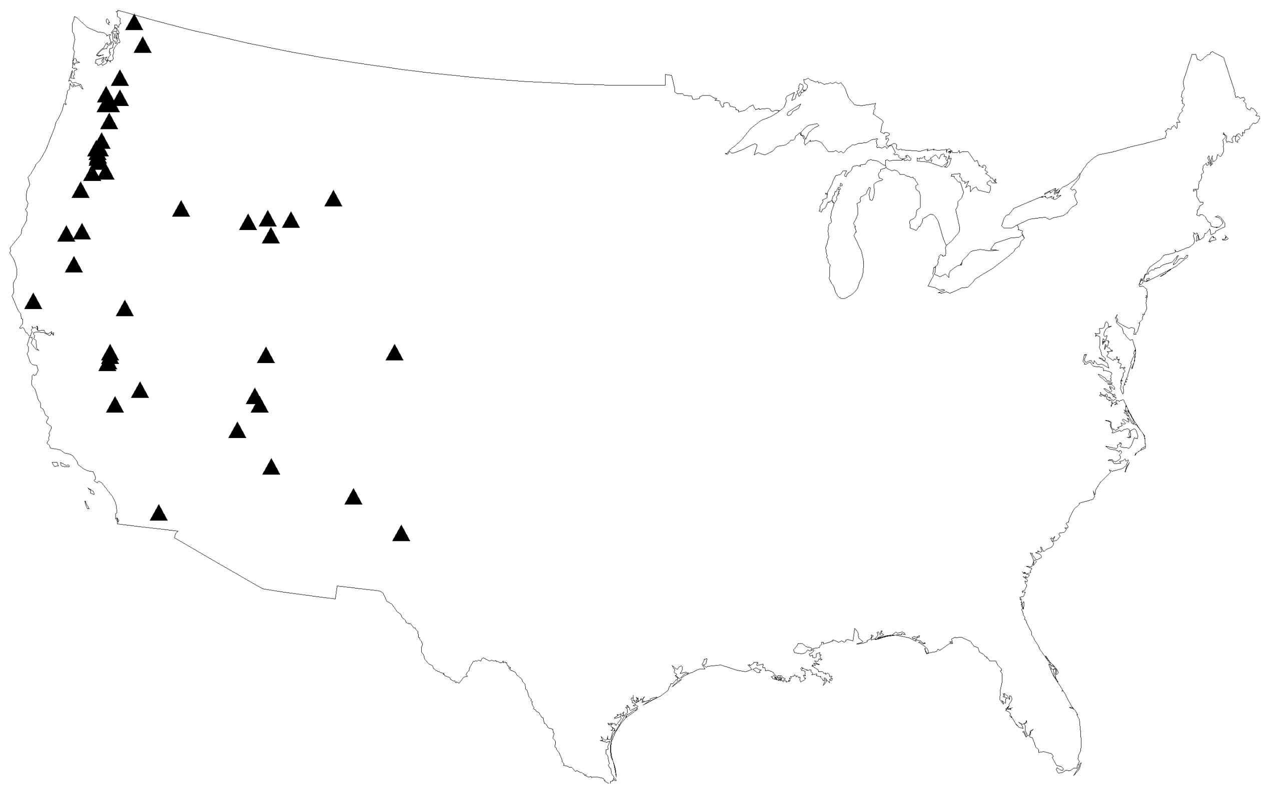

Figure B-6: Approximate locations of Holocene volcanic activity. Proposed sites located near these locations may require additional analysis and evaluation (Siebert and Simkin, 2002)

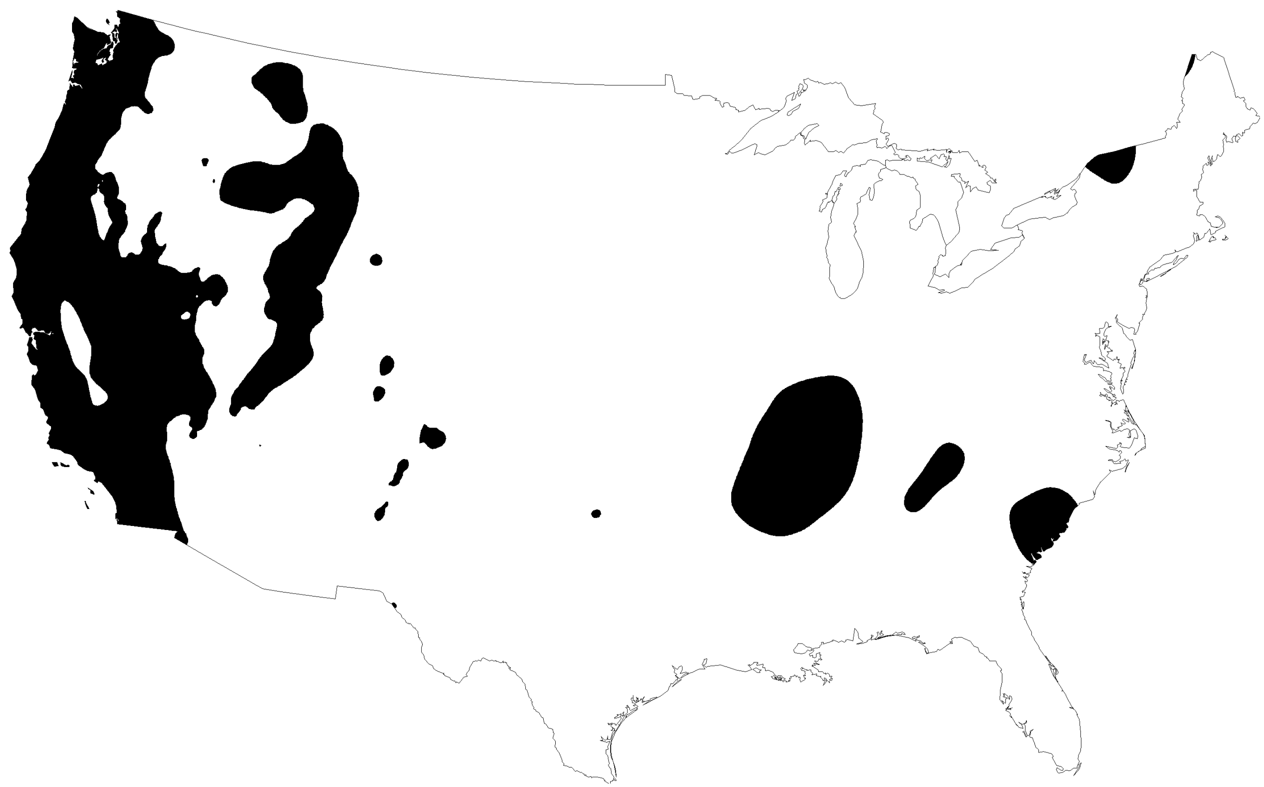

Figure B-7: Current approximate areas of higher potential seismic hazard. Proposed sites located near these areas may require additional analysis and evaluation (Petersen et al, 2011)

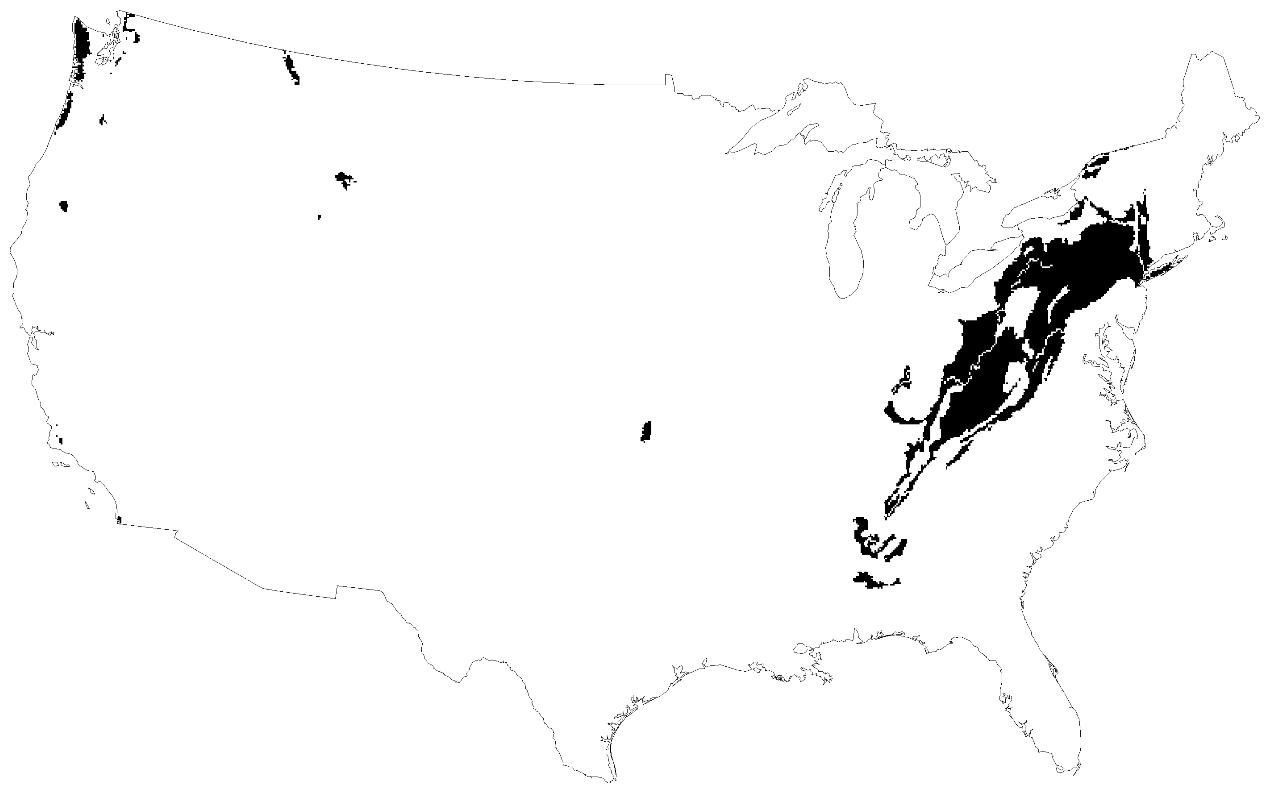

Figure B-8: Current approximate areas of higher vulnerability to water erosion. Proposed sites located in these areas may require additional site characterization and analysis. Areas of high vulnerability to water erosion in the future may change (USDA, 1988)

Figure B-9: Approximate area covered by glaciers during the last three glacial periods of the current Quaternary ice age, i.e., the Wisconsin, Illinoisan, and Pre- Illinoisan glacial periods. Glaciers can cause very disruptive surface geologic processes and potential sites located in areas created by previous glacial processes could require additional analysis and careful evaluation (Ehlers et al., eds., 2011)

REFERENCES

Ehlers et al., 2011. Ehlers J., P.L. Gibbard, and P.D. Hughes, eds., “Quaternary Glaciations - Extent and Chronology: A closer look", Vol. 15, 1st Ed., ISBN: 9780444534477. [http://booksite.elsevier.com/9780444534477/DCW_North_America_wgs84_1.php and http://booksite.elsevier.com/9780444534477/DCW_North_America_wgs84_2.php]

ESRI, 2008a. Environmental Systems Research Institute, Inc., “Data & Maps and StreetMap – North America DVD,” U.S. National Atlas Water Feature Areas, ArcGIS 9, ESRI Data & Maps 9.3, April 1, 2008.

ESRI, 2008b. Environmental Systems Research Institute, Inc., “Data & Maps 9.3, Elevation and Image Data - World DVD,” U.S. Geological Survey Center for Earth Resource Observation and Science (EROS), ArcGIS 9, ESRI, April 1, 2008.

FEMA, 1998. Federal Emergency Management Agency, National Flood Insurance Program Q3 Flood Data, September 1998, Washington D.C.

FEMA, 2012. Federal Emergency Management Agency, National Flood Hazard Layer on DVD, Washington D.C.

Kreakie et al., 2012. Kreakie, B.J., Y. Fan, and T.H. Keitt, ”Enhanced Migratory Waterfowl Distribution Modeling by Inclusion of Depth to Water Table Data,” PLoS ONE 7(1): e30142, doi:10.1371/journal.pone.0030142, 2012. [http://www.plosone.org/article/info:doi/10.1371/journal.pone.0030142]

Petersen et al., 2011. Petersen, M.D., A.D. Frankel, S.C. Harmsen, C.S. Mueller, K.M. Haller, R.L. Wheeler, R.L. Wesson, Yuehua Zeng, O.S. Boyd, D.M. Perkins, Nicolas Luco, E.H. Field, C.J. Wills, and K.S. Rukstales, “Seismic-hazard maps for the conterminous United States,” U.S. Geological Survey, 2008 Scientific Investigations Map 3195, 2011. [http://pubs.usgs.gov/sim/3195/]

Siebert and Simkin, 2002. Siebert L. and T. Simkin, “Volcanoes of the World: an Illustrated Catalog of Holocene Volcanoes and Their Eruptions,” Smithsonian Institution, Global Volcanism Program Digital Information Series, GVP-3, 2002.

USDA, 1998. U.S. Department of Agriculture, “Water Erosion Vulnerability Map,” Natural Resources Conservation Service (NRCS), 1998.

USGS, 2011. U.S. Geological Survey, Multi-Resolution Land Characteristics Consortium (MRLC), National Land Cover Database (NLCD), National Land Cover Database 2006 (NLCD2006), 20110216, 2011. [http://www.mrlc.gov/nlcd06_data.php]

APPENDIX C
GENERIC FEATURES, EVENTS, AND PROCESSES LIST FOR NEAR-SURFACE DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE

The NRC staff has developed a generic FEPs list that can be used by reviewers, applicants, licensees, and other interested stakeholders involved with preparation and review of technical analyses conducted to support licensing of a near-surface low-level radioactive waste (LLW) disposal facility. The NRC staff consulted numerous references to develop (1) a comprehensive list of FEPs, and (2) a smaller set of FEPs (or “starter list”) that need to be analyzed and screened based on requirements in 10 CFR Part 61 and are usually considered to be essential to development of performance assessment (PA) analyses. The starter FEP list should not be considered a complete FEP list. Rather, it is a core list of FEPs that any LLW PA should consider for screening. There are various methods of screening FEPs as described in Section 2.0. The level of technical analysis needed to justify exclusion of a required FEP or needed to evaluate the impact of an included (or “screened in”) FEP (or set of FEPs) can vary. The level of effort expended on disposition or evaluation of the FEP(s) should be commensurate with the expected risk-significance of the FEP (or group of FEPs that form a central or alternative scenario). A complete set of site-specific FEPs can only be developed from an adequate understanding of the disposal system that is gained through site characterization and review of detailed facility designs. Development and evaluation of FEPs is considered an iterative process, beginning first with evaluation of a central scenario that incorporates all of the key FEPs that best represent the dynamic system being studied. Following initial analyses, alternative scenarios that might include potential disruptive events should also be considered, as appropriate; to ensure that potential vulnerabilities in disposal system performance are identified and adequately addressed. As-emplaced conditions (including final engineered barrier configurations and waste allocation), monitoring, and other data developed following initial PA preparation, should also be considered to ensure that the results of the PA adequately assess the risk of the disposal facility. The starter list of FEPs that should be addressed in LLW PAs is provided in Table C-1.

Table C-1 Starter FEPs List for Near-Surface Disposal in the United States

Type	FEP
Feature	Radiological inventory
	Waste inventory
	Wasteform (e.g. design, properties, characteristics)
	Waste container
	Free liquids
	Colloids
	Backfill
	Disposal unit
	Disposal site
	Buffer zone
	Engineered barriers (e.g. intruder barriers, engineered cover):
	Presence of agents in waste that may increase mobility (e.g., chelating agents) or lead to degradation of engineered barriers (e.g., corrosive agents)
	Material defects
	Geologic units and materials: Surface soils and sediments Stratigraphy and lithology Hydrogeologic units
	Surface water
	Preferential pathways (anthropogenic, natural)
	Perched water
	Wetlands
	Biosphere: Humans Ecology Flora and fauna (including insects)
	Receptors – surrounding population
	Exposure pathways
	Land use
	Institutional control
	Natural resources
Process	Climate and meterology
	Natural climate cycling (e.g. glaciation)
	Radioactive decay and in-growth
	Waste interactions
	Gas generation
	Radon emanation
	Waste release (e.g. leaching, dissolution)
	Pyrophoricity
	Criticality
	Degradation: Corrosion – all forms Creep Fatigue Abrasion (wind, water) Temperature cycling or extremes Freeze thaw cycling

Table C-1 Starter FEPs List for Near-Surface Disposal in the United States

Type	FEP
	Frost action Wet/dry cycling Salt action Oxidation Acid attack Weathering Fracturing (via mechanical or chemical/reaction) Cementitious material degradation Geosynthetic degradation processes Plugging of drainage layers Degradation of clays (e.g. dessication) Polymer degradation Seismic-induced degradation
	Internal degradation processes, to waste and disposal units: Biodegradation Reaction – incompatible materials Thermodynamic instability Excessive void space – subsidence Radiation damage Dissolution Internal stress generation
	External degradation processes, interaction of system with environment
	Geochemical evolution (disposal unit, disposal site, surrounding environment)
	Geochemistry – speciation, solubility, sorption, etc.
	Interactions of environment and disposal system
	Biological driven release (plant uptake, burrowing animals, biotrubation, etc.)
	Ecological succession
	Water balance processes (e.g. evapotranspiration, runoff, recharge)
	Infiltration
	Near-field flow processes (e.g. flow bypassing, film flow)
	Episodic flow
	Groundwater flow: Advection Dispersion Water table fluctuation Discharge to surface Matrix diffusion Dilution Diffusion Density-driven flow Capillary rise
	Erosion
	Deposition
	Instability
	Geomorphology
	Surface geologic processes – mass wasting, subsidence, slope failure, etc.
	Dynamic change to geology (e.g. sinkhole formation)
	Loading and differential settlement

Table C-1 Starter FEPs List for Near-Surface Disposal in the United States

Type	FEP
	Pedogenesis
	Tectonic processes
	Groundwater transport
	Gas transport
	Soil transport (fluvial, aeolian)
	Colloid transport
	Dose assessment processes (e.g. drinking water consumption, soil build-up, resuspension)
	Dynamic processes (e.g. natural temporal variability, seasonal effects, episodic changes, barometric pumping)
Event	Explosion
	Fire
	Inadvertent human intrusion (habitation, drilling, resource exploration)
	Accident – operational or external
	Dam failure
	Aircraft crash
	Tectonic events: Seismic (including earthquakes) Volcanic Tsunami
	Tornado
	Hurricane

As discussed above, a comprehensive generic FEPs list appropriate for near-surface disposal of low-level radioactive waste was developed for use by reviewers, applicants, licensees, and other interested stakeholders. A number of references were consulted during development of this list (NEA, 2000; NEA, 2006; IAEA, 2003, BIOMOVS II, 1996; Arlt, 2013; Neptune, 2011; SRS, 2012a; SRS, 2012b). Some of the reference FEPs are not expected to be risk-significant during the time periods of interest for disposal of most LLW or are considered outside the scope of the 10 CFR Part 61 regulatory framework. An effort was made to identify classes of these FEPs. For those FEPs sources that screened FEPs in or out (e.g., BIOMOV and site-specific FEPs lists), the rationale for exclusion of the FEP was considered in determining whether to list the FEP in the generic FEPs list. It is important to note that although a project-specific FEP may have been “screened out”, if the FEP was considered potentially applicable to near-surface LLW disposal, it was included in the generic FEP list. Although screening approaches and the results of screening are summarized below, it is important to note that no effort was made to evaluate the adequacy of FEP screening processes discussed, nor the completeness of project-specific FEP lists.

The comprehensive, generic FEPs list is structured after the Improvement of Safety Assessment Methodologies (ISAM) and Nuclear Energy Agency (NEA) FEPs lists described in more detail below. FEPs that may be considered unlikely during the compliance period but may become increasingly more likely over time are flagged as “long-term” FEPs. If a FEP is designated a “long-term” FEP the applicability of the FEP for a specific site should be considered by licensees when performance period analyses are required. Although some FEPs from the reference sources are not explicitly listed in the generic FEP list, one can assume that the FEP should be considered unless it is clearly linked to a category of FEPs that are not considered important for near-surface waste disposal.

Reference sources used to create the generic FEPs list include databases developed by international standards setting organizations, as well as several site-specific applications for low- and high-level radioactive waste disposal facilities (or repositories) in the United States and indirectly, Europe[1]. A brief description of each of these data sources is provided first below.

<u>BIOMOVs II</u>

A structured, generic biosphere FEP list was developed by the BIOMOVS II Reference Biospheres Working Group. BIOMOVS is an international study to test models designed to predict the environmental transfer and bioaccumulation of radionuclides and other trace substances. The BIOMOVS II FEP list was developed specifically for application to the calculation of annual individual doses arising at an inland site from long-term release of radionuclides to groundwater. The list is, nonetheless, relevant to a wide range of assessments. The developers recognized that the list may not include sufficient detail for any specific project or assessment. Additionally, definitions may not be universally applicable. The structure of the FEPs list is provided in Figure C-1. The expanded FEPs list includes approximately 140 FEPs.

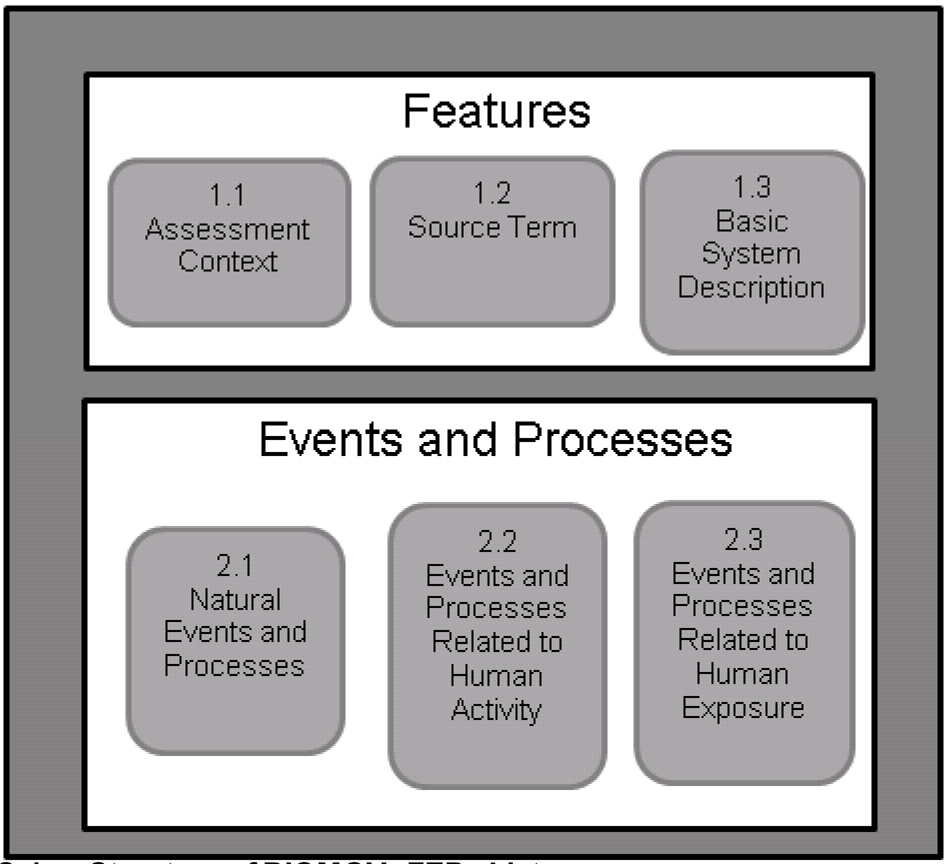

Figure C-1 Structure of BIOMOVs FEPs List

[1] Several domestic FEP lists incorporate FEPs from European assessments.

Nuclear Energy Agency

The Nuclear Energy Agency (NEA) developed an international FEPs list (2000) relevant to the post-closure safety of repositories for solid radioactive waste. The NEA FEPs list was intended to (i) provide a list of FEPs to be considered when determining the scope of a new assessment; (ii) provide a list of FEPs against which completed assessments could be audited or reviewed; and (iii) provide confidence in the comprehensiveness of a completed assessment. A list of 134 FEPs were provided in the NEA FEPs list (2000).

A database was created to facilitate use of the international FEPs list, consisting of two parts:

1. The International FEP List—the structured list of factors, or FEPs, relevant to the assessment of the long-term safety of nuclear waste repositories.
2. Project Databases—a collection of FEPs lists and databases from specific project studies, along with their references.

The database was developed by the NEA FEP Database Working Group that included representatives from seven, Organization for Economic Cooperation and Development (OECD)/NEA countries. Version 2.1 of the database contains over 1650 project-specific FEPs[2] from 10 projects (2006). Two additional project-specific FEPs lists were added: (i) SCK-CEN Catalogue of Events, Features and Processes for the Mol Site in Belgium and (ii) Encyclopedia of FEPs for the Swedish SFR and Spent Fuel Repositories. Additional details on the project specific FEPs lists and additional functionality were added to the database. The NEA international FEPs list can be considered a generic, high-level FEPs list from which project-specific FEPs could be developed or categorized. Project-specific FEPs available in the database are cross-walked back to the categorical FEPs comprising the international FEPs list. The major categories of the NEA international FEPs list are provided in Figure C-2. The international FEPs list has 4 layers with the 3 inner layers in Figure C-2 further subdivided into additional categories. Not listed in Figure C-2 are individual FEPs for each subcategory.

IAEA ISAM

In 1997, the IAEA launched a coordinated research project on Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM) to critically evaluate, enhance, and provide confidence in the approaches and tools used for post-closure safety assessments of near-surface radioactive waste disposal facilities. As part of the ISAM project, the NEA international FEPs list was modified for near surface disposal facilities. For example, some of the NEA FEP definitions and comments associated with the FEPs were altered to be more representative of near surface conditions. The ISAM FEPs list was intended to be a user-friendly list. The ISAM FEPs list was also intended to be a comprehensive, initial list from which FEPs applicable to any specific site could be developed. Because the NEA list was extensively reviewed for completeness for geologic systems and the ISAM FEPs lists was based on the NEA FEPs list, the developers of the ISAM FEPs list reasoned that users should have additional confidence in the comprehensiveness of the ISAM FEPs list. Additionally, experience with both specific near surface disposal facilities and FEPs lists developed and applied in the ISAM test cases was used in the development of the ISAM FEPs list. The hierarchy of the ISAM FEPs list is similar to that of the NEA international FEPs list in Figure C-2[3].

[2] These project FEPs are not unique and many of them overlap.
[3] This is true with the exception that "1.5 Other External Factors" is not included in the ISAM FEPs list.

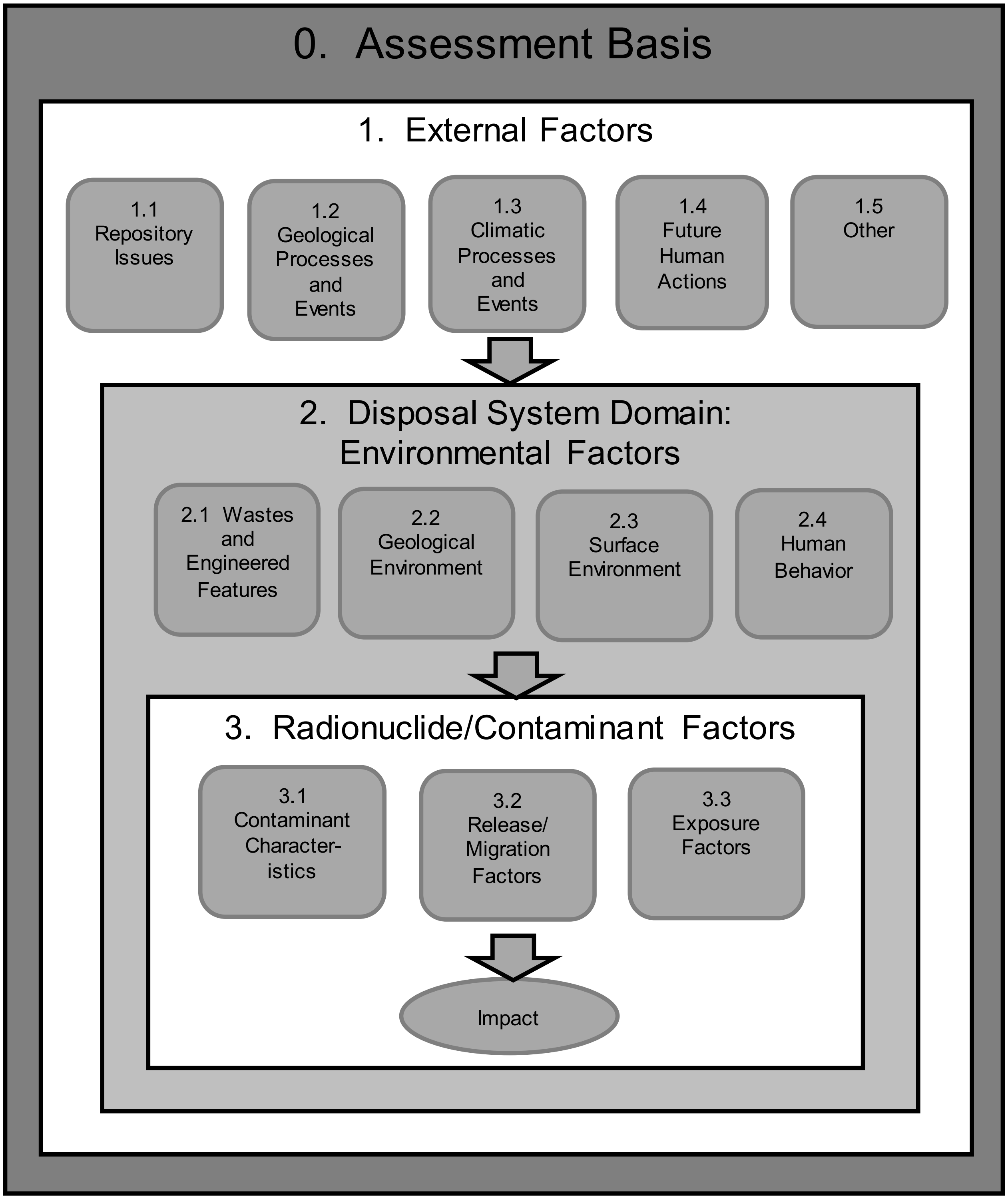

Figure C-2 Structure of the NEA FEPs list

BIOMASS

Changes were made to the organization of the BIOMOVS II list described above in developing the BIOMASS FEPs list. These changes include the following:

- A clearer distinction between FEPs related to basic elements of the assessment context and those related to the biosphere system, radionuclide transport and radiation exposure.
- The expression of intrinsic phenomena relating to the biosphere system in terms of characteristics of the system, rather than the behavior of radionuclides within the system. Those FEPs that relate to radionuclide behavior can (where necessary) be incorporated in the respective definitions. FEPs that are related solely to the presence of radionuclides within the system (e.g. radiation exposures) are then clearly identified under a separate heading.
- Experience gained with the application of the reference biosphere methodology since BIOMOVS II, which has helped to amplify certain details of the original list and led to the incorporation of additional FEPs.

Department of Energy (DOE) Hanford site

The Hanford Site is an approximately 586 mi^2 area north of the city of Richland within the semiarid Pasco Basin of the Columbia Plateau in southeastern Washington State. Hanford occupies a relatively undeveloped area of shrub-steppe (a drought-resistant, shrub and grassland ecosystem) that contains a rich diversity of plant and animal species. The area has been protected from disturbance, except for fire, over the past 60 years. This protection has allowed plant species and communities that have been displaced by agriculture and development in other parts of the Columbia Basin to thrive at the Hanford Site. The Columbia River flows eastward through the northern part of the Hanford Site and then turns south, forming part of the eastern site boundary. Other important rivers near the Hanford Site are the Yakima River to the south and southwest and the Snake River to the east. The Cascade Mountains, which are about 160 km (100 mi) to the west, have an important effect on the climate of the area.

In 1943, the U.S. Army Corps of Engineers created the Hanford Site from small farming areas along the Columbia River to locate facilities used to produce nuclear weapon materials for World War II. Since then, the major activities on the Hanford Site have been controlled by DOE and its predecessors. Current major programs at the Hanford Site are dedicated to waste management, environmental restoration, long-term stewardship, and research and development. Fuel reprocessing, plutonium and uranium separation, plutonium finishing, and waste management, including treatment, storage, and disposal activities have been conducted in the 200 Area of the site.

There are a total of 177 underground tanks located in the 200 Area of the site used to store reprocessed, liquid high-level waste from reactor operations and other site activities. DOE has initiated the process of retrieving, treating, and disposing of radioactive mixed waste from 149 underground single-shell tanks that do not have secondary containment. DOE Hanford prepared a performance assessment (PA) to support closure of these tanks. In 2009, DOE Hanford initiated a scoping process to assist with updating the PA to support tank closure. An extensive FEPs list was developed as part of this scoping process. Due to lack of funding the scoping process was curtailed; however, the draft list of FEPs developed during Hanford PA scoping was considered in this study.

Clive, Utah Site

The Clive, Utah low-level waste disposal facility is operated by Energy Solutions. Energy Solutions prepared a PA to evaluate the risk of disposal of depleted uranium (DU) waste. To support PA development, Energy Solution developed a list of FEPs. Neptune (2011) documents and examines the universe of FEPs that may apply to the disposal of DU waste at the Clive Facility. The identification of FEPs for use in the Clive facility PA was an iterative process that began with compilation of an exhaustive list of candidate FEPs that could affect the long-term performance of the low-level waste disposal facility. Table C-2 lists the reference sources considered in developing the initial list of FEPs. As an initial step, all potentially relevant FEPs from a variety of reference sources were collected (e.g., Yucca Mountain Project, the Waste Isolation Pilot Plant, and several foreign radioactive waste projects). The initial list from external sources was modified as additional FEPs were identified that are specific to the Clive facility. Approximately 980 FEPs were identified.

This exhaustive compilation of FEPs led to significant redundancy across the original sources. Redundancy was addressed by the modification of the candidate list of FEPs through normalization (removal of redundant FEPs) and assignment of FEPs categories (groupings of common FEPs). This consolidation process reduced the total number to 135 unique FEP groupings. These 135 unique FEP groupings were binned into 18 major categories.

Of the 135 FEP groupings, 67[4] FEP groupings were retained for further consideration and 68[5] FEP groupings were dismissed from inclusion in the PA model. All FEP groupings considered and retained for inclusion in the conceptual site model (CSM) and scenarios are reported in Table C-3 (see unshaded FEPs). FEPs that were dismissed from consideration in the PA include those that do not fall within the scope of the PA, were characterized as extremely unlikely to occur or having a low magnitude of consequence of affecting the performance of the disposal facility, or were dismissed based on site-specific considerations. FEP groupings that were excluded from the PA are also listed in Table C-3 (see grey shaded FEPs).

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[4] Neptune (2011) indicates in text that 90 FEP grouping were retained but only 67 FEP groupings are actually listed in Table B of the same document.

[5] Neptune (2011) indicates in text that 45 groupings were excluded but 68 FEP groupings are actually listed in Table C of the same document.

Table C-2 List of Clive Facility FEPs Reference Sources

Project or Facility	Reference
SKI/SKB	Andersson, J., T. Carlsson, T.F. Kautsky, E. Soderman, and S. Wingefors, 1989. *The Joint SKI/SKB Scenario Development Project*. SKB-TR8 9-35, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.
WIPP	Burkholder, H.C., 1980. *Waste Isolation Performance Assessment—A Status Report*, in Scientific Basis for Nuclear Waste Management, Ed. C.J.M. Northrup, Jr., Plenum Press, New York, NY, Vol. 2, p. 689-702.
WIPP	Guzowski, R.V., 1990. *Preliminary Identification of Scenarios That May Affect the Escape and Transport of Radionuclides From the Waste Isolation Pilot Plant, Southeastern New Mexico*, SAND89-7149, Sandia National Laboratories, Albuquerque, NM.
NTS	Guzowski, R.V., and G. Newman, 1993. *Preliminary Identification of Potentially Disruptive Scenarios at the Greater Confinement Disposal Facility, Area 5 of the Nevada Test Site*, SAND93-7100, Sandia National Laboratories, Albuquerque, NM.
NTS	Hertzler, C.L., and C.L. Atwood, 1989. *Preliminary Development and Screening of Release Scenarios for Greater Confinement Disposal of Transuranic Waste at the Nevada Test Site*, EGG-SARE-8767, EG&G Idaho, Inc., Idaho Falls, ID.
Hypothetical Columbia Plateau Repository	Hunter, R.L., 1983. *Preliminary Scenarios for the Release of Radioactive Waste From a Hypothetical Repository in Basalt of the Columbia Plateau*, SAND83-1342 (NUREG/CR-3353), Sandia National Laboratories, Albuquerque, NM.
WIPP	Hunter, R.L., 1989. *Events and Processes for Constructing Scenarios for the Release of Transuranic Waste From the Waste Isolation Pilot Plant*, Southeastern New Mexico, SAND89-2546, Sandia National Laboratories, Albuquerque, NM.
HLW Repository	IAEA, 1983. *Concepts and Examples of Safety Analyses for Radioactive Waste Repositories in Continental Geological Formations*, Safety Series Report No. 58, IAEA, Vienna.
HLW Repository	Koplik, C.M., M.F. Kaplan, and B. Ross, 1982. *The Safety of Repositories for Highly Radioactive Wastes*, Reviews of Modern Physics, Vol. 54, No. 1, p. 269-310.
HLW Repository (Canada)	Merrett, G.J., and P.A. Gillespie, 1983. *Nuclear Fuel Waste Disposal: Long-Term Stability Analysis*, AECL-6820, Atomic Energy of Canada Limited, Pinawa, Manitoba.
NEA Working Group	NEA (Nuclear Energy Agency), 1992. *Systematic Approach to Scenario Development. A report of the NEA Working Group on the Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal*, Nuclear Energy Agency, Paris, France.
NEA Working Group	NEA, 2000. *Features, Events, and Processes (FEPs) for Geologic Disposal of Radioactive Waste. An International Database*. Nuclear Energy Agency, Organization for Economic Cooperation and Development.

[1] References for Andersson et al. (1989), Burkholder (1980), Guzowski (1990), Hertzler and Atwood (1989), Hunter (1983), Hunter, (1989), IAEA (1983), Koplik et al. (1982), Merrett and Gillespie, NEA (1992) and Prij et al. (1991) were found in Guzowski and Newman (1993).

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
1	Model Settings	Model Parameterization
2		Period of Performance
3		Regulatory Requirements
4		Spatial Domain
5	Geological	Diagenesis
6		Gas or Brine Pockets
7		Landslide
8		Local Subsidence
9	Geochemical	Geochemical Effects
10	Hydrogeological	Denudation
11		Erosion
12		Erosional Transport
13		Hydrogeological Effects
14		Sedimentation
15		Subrosion
16	Hydrology	Groundwater Transport
17		Hydrological Effects
18		Inundation
19		Flooding
20		Surface Water Transport
21	Meteorology	Frost Weathering
22		Meteorology
23		Resuspension
24		Atmospheric Dispersion
25		Tornado
26	Marine	Coastal Processes
27		Hurricanes
28		Insolation
29		Marine Effects
30		Tsunami
31	Climate Change	Climate Change
32		Lake Effects
33		Wave Action
34		Glacial Effects
35		Permafrost
36	Tectonic/Seismic/Volcanic	Geophysical Effects
37		Breccia Pipes
38		Diapirism
39		Discontinuities
40		Earthquake
41		Faulting
42		Fracturing
43		Geological Intrusion
44		Hydraulic Fracturing

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
45		Instrusion Into Accumulation Zone in the Biosphere
46		Isostatic Effects
47		Lava Tubes
48		Orogeny
49		Regional Subsidence
50		Seismic Effects
51		Tectonic Effects
52		Volcanism
53	Celestial	Meteorite Impact
54	Natural Processes	Microbial Effects
55		Radiological Effects
56		Wildfire
57	Other Natural Processes	Ecological Changes
58		Gas Generation
59		Pedogenesis
60		Radioactive Decay and In-growth
61		Radon Emanation
62		Reconcentration
63	Human Processes	Anthropogenic Climate Changes
64		Community Development
65		Excavation
66		Explosions
67		Human-Induced Processes
68		Human-Induced Transport
69		Inadvertent Human Intrusion
70		Inhabitation
71		Institutional Control
72		Land Use
73		Post-Closure Subsurface Activities
74		Accidents During Operations
75		Climate Control
76		Closure Failure
77		Fire
78		Fisheries
79		Geothermal Energy Production
80		Injection Wells
81		Intentional Intrusion
82		Investigation
83		Irrigation
84		Monitoring
85		Nuclear Testing
86		Operational Effects
87		Operational Error

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
88		Quality Control
89		Resource Extraction
90		Sabotage
91		Unplanned Events
92		War
93		Waste Recovery
94		Water Resource Management
95		Weapons Testing
96	Containerization	Containment Degradation
97		Corrosion
98	Engineered Features	Compaction Error
99		Engineered Features
100		Material Properties
101		Repository Design
102		Source Release
103		Subsidence of Repository
104		Waste
105	Waste	Nuclear Criticality
106		Other Waste
107	Source Release	Electrochemical Effects
108		Explosions
109	Contaminant Migration	Biotically-Induced Transport
110		Colloid Transport
111		Contaminant Transport
112		Diffusion
113		Dilution
114		Dispersion
115		Dissolution
116		Dust Devils
117		Gas Transport
118		Infiltration
119		Local Geology
120		Preferential Pathways
121		Gas Intrusion
122		Convergence of Opening
123		Design Error
124		Material Defects
125		Mechanical Effects
126		Release of Stored Energy
127		Repository Seals
128	Exposure	Animal Ingestion
129		Dosimetry
130		Exposure Media
131		Human Behavior

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
132		Human Exposure
133		Ingestion Pathways
134		Inhalation Pathways
135		Agriculture

DOE Savannah River Site (SRS)

SRS is a 780 km^2 (300 mi^2) DOE facility located approximately 12 miles south of Aiken, South Carolina, and 15 miles southeast of Augusta, Georgia. The SRS region is characterized as a humid subtropical climate with relatively short, mild winters and long, warm, and humid summers. Summer-like conditions typically last from May through September, when the area is frequently under the influence of a western extension in the semi-permanent Atlantic subtropical anticyclone (i.e., the 'Bermuda' high). The influence of the Bermuda high begins to diminish during the fall as continental air masses become more prevalent, resulting in lower humidity and more moderate temperatures. Less than one-third of winter days have minimum temperatures below freezing on average, and days with temperatures below 20°F are infrequent. Measurable snowfall occurs an average of once every two years.

Operation at SRS began in 1951. The primary use for the site was the production of nuclear material for national defense. Between 1954 and 1986, DOE generated significant quantities of radioactive waste from the reprocessing of spent nuclear fuel and to a lesser extent from the production of targets for nuclear weapons and material for space missions. This waste was stored in 51 underground tanks located in two tank farms: F-Tank Farm (FTF) contains 22 tanks and H-Tank Farm houses 29 tanks. DOE plans to clean the tanks and stabilize the waste residuals in a cementitious wasteform. DOE also plans to dispose of relatively low-activity salt waste retrieved from the tanks in the saltstone disposal facility. DOE has prepared PAs to demonstrate that the stabilized waste remaining in the tank farms and the waste disposed of in the saltstone disposal facility can meet performance objectives for low-level waste disposal. DOE prepared an *ex post facto* FEPs analysis to provide support for its compliance demonstrations.

The initial, SRS FEPs list included 245 FEPs drawn from five different reference sources listed in Table C-4. The initial 245 FEPs were then binned into six categories listed in Table C-5.

Table C-4 SRS FEP List Reference Sources

FEPs List	Source Document	Total Number of FEPs
ISAM	*Safety Assessment Methodologies for Near-Surface Disposal Facilities*, Results of a Coordinated Research Project, Volume 1 [ISBN 92-0-104004-0]	141
UFD	*Features, Events, and Processes for the Disposal of Low Level Radioactive Waste FY2011 Status Report* [FCRD-USED-2011-000297]	449
YMP	*Features, Events, and Processes for the Total System Performance Assessment: Analyses* [ANL-WIS-MD-000027 REV 0]	374
DGR	*Deep Geologic Repository for OPG's Low and Intermediate Level Waste, Post-Closure Safety Assessment (Volume 1): Features, Events and Processes* [NWMODGR-TR-2009-05]	299
SKI	*Encyclopedia of Features, Events and Processes (FEPs) for the Swedish SFR and Spent Fuel Repositories* [SKI Report 02:35]	120

Table C-5 SRS FEPs List Categories

Category	Group
1.0 Assessment Basis	1.1 General
	1.2 Regulations and Controls
	1.3 Models and Calculations
	1.4 Other Assessment Factors
2.0 External Factors	2.1 Human Characteristics
	2.2 Land and Water Management
	2.3 Future Human Activity
	2.4 Biological Factors
	2.5 Geologic Features
	2.6 Geologic Processes
	2.7 Climate
	2.8 Water Cycle
3.0 Closure System	3.1 General Closure System
	3.2 Pre-Closure Activities
	3.3 Closure System Components
	3.4 Closure System Hydrology
	3.5 Chemical Processes
	3.6 Thermal Processes
	3.7 Material Degradation
	3.8 Other Closure System Factors
4.0 Contaminant Factors	4.1 Contaminant Description
	4.2 Contaminant Properties
	4.3 Concentrations
	4.4 Exposure Factors
	4.5 Other Contaminant Factors
5.0 Flow and Transport	5.1 Flow Factors
	5.2 Hydraulic Effects on Flow
	5.3 Release and Transport
6.0 Disruptive Events	6.1 Intrusions
	6.2 Seismic Events
	6.3 Igneous Events
	6.4 Other Events

In addition to consolidation of the 5 FEPs list reference sources, DOE included 17 additional FEPs evaluated in SRS PAs leading to a total of 262 FEPs. Next, the list of 262 FEPs was screened[6]. The SRS FEPs screening team performed screening in two phases. During the first phase, team members independently applied the FEPs screening criteria[7] via survey. The independent survey results were collected and a subset of FEPs was “screened in” or “out” based on the results. Those FEPs with relatively more ambiguous results (i.e., survey results indicated that FEP should be considered further) were discussed in the second phase. At the

[6] This is true except for 46 programmatic FEPs that would not be subject to screening. These FEPs are listed in Table 4.0-1 of SRR-CWDA-2012-00011, Revision 0.

[7] Criteria were based on the perceived probability of occurrence within 10,000 years and the perceived consequence relative to final PA results.

start of Phase 2, 142 FEPs remained. The FEPs that were “screened out” in Phase 1 and 2 are listed in Table C-6.

A total of 230 FEPs remained after Phase 2 screening. SRR-CWDA-2012-00022 crosswalks remaining FEPs to the FTF PA to ensure all relevant FEPs were addressed.

Table C-6 FEPs Excluded from SRS PAs

FEP	ID	Phase
Large Scale Salt Processes (Diapirism, Dissolution, and Creep)	2.6.11	Phase 1
Ashfall	6.3.03	Phase 1
Extraterrestrial Events	6.4.08	Phase 1
Changes in the Earth's Magnetic Field	6.4.09	Phase 1
Changes to Earth's Tidal Processes	6.4.10	Phase 1
Pollution (Soil, Groundwater, Air, etc.)	2.2.07	Phase 2
Ozone Layer Failure	2.3.07	Phase 2
Species Evolution	2.4.05	Phase 2
Stress Regimes	2.5.09	Phase 2
Orogeny	2.6.03	Phase 2
Diagenesis and Pedogenesis	2.6.05	Phase 2
Sedimentation	2.6.06	Phase 2
Creeping of the Rock Mass	2.6.10	Phase 2
Acid Rain	2.7.04	Phase 2
Costs of Construction, Operation, Closure	3.2.04	Phase 2
Chelating Agent Effects	3.5.12	Phase 2
Thermal Processes and Conditions the Engineered System	3.6.01	Phase 2
Thermal Processes and Conditions the Natural System	3.6.02	Phase 2
Thermo-Mechanical Stresses Alter Characteristics of Engineered Barrier System Components	3.6.04	Phase 2
Recrystallization of Vitrified Wastes	3.6.05	Phase 2
Effects of System Heat on the Biosphere	3.6.06	Phase 2
Creep of Metallic Materials in the Engineered System	3.7.04	Phase 2
Oxygen Embrittlement of Engineered System Metals	3.7.05	Phase 2
Localized Interactions Between Emplaced Wastes	4.2.05	Phase 2
Nuclear Criticality	4.5.01	Phase 2
Chemically-Induced Density Effects on Groundwater Flow	5.1.06	Phase 2
Hydrothermal Activity	5.2.02	Phase 2
Seismicity Associated with Igneous Activity	6.2.04	Phase 2
Igneous Intrusion Into the Closure Facility	6.3.01	Phase 2
Volcanic Eruptions and Magmatic Activity	6.3.02	Phase 2
Releases Prior to Closure	6.4.01	Phase 2
Impacts from Meteorites or Space Debris	6.4.07	Phase 2
Extraterrestrial Events	6.4.08	Phase 2
Changes in the Earth's Magnetic Field	6.4.09	Phase 2
Changes to Earth's Tidal Processes	6.4.10	Phase 2

Generic FEPs List

The ISAM and NEA international FEP list structure illustrated in Figure C-2 above was retained in constructing a comprehensive, generic FEP list applicable to near-surface disposal of LLW. Because the ISAM FEP list modified the NEA FEP list to be more applicable to near-surface disposal facilities, the ISAM FEP category titles are specifically listed in the generic FEP list. However, some FEPs of the ISAM FEPs are not expected to be risk-significant during the time periods of interest for disposal of most LLW in the United States or are considered outside the scope of the 10 CFR Part 61 regulatory framework. These FEPs that are considered less relevant for near-surface disposal of LLW are listed in Table C-7. The remaining ISAM FEPs represent the major FEP groupings in the generic FEPs list (see column 1).

The generic FEPs list comprises three separate tables: (i) assessment context or operational factors (see Table C-8) used to develop FEPs presented in Tables C-9 and C-10, (ii) FEPs to analyze or screen to construct central and alternative scenarios presented in Table C-9, and (iii) FEPs to analyze or screen for receptor scenarios presented in Table C-10. Table C-8 factors are not FEPs per se, but assessment context (e.g., purpose of the assessment), operational factors, and site characterization or monitoring activities may dictate the types and scope of FEPs considered in a technical assessment. Therefore, Table C-8 factors are listed and expected to be valuable considerations in the development of project-specific FEPs.

FEPs that may be considered unlikely during the compliance period or protective assurance period but may become increasingly more risk-significant over time are flagged “long-term” in column 3 of Tables C-9 and Table C-10 (no assessment context factors are marked long-term). If the “long-term” column is marked in column 3, the applicability of the FEPs for a specific site should be considered when performance period analyses are required for that site. Although some FEPs from the reference sources are not explicitly listed in Tables C-7 through C-10, one can assume that the FEP should be considered unless it is clearly linked to a category of FEPs that are not considered applicable for near-surface waste disposal listed in Table C-7. Reviewers, applicants, licensees, and other interested stakeholders should find the level of detail provided in tables sufficient to understand the scope of FEPs that should be considered for any site with many examples provided in the last column (column 4); however, the generic FEP list should not be considered an exhaustive list that would encompass every potentially applicable FEP that may be important for a particular site. Likewise, not every FEP listed in Tables C-8 through C-10 would need to be considered by a licensee.

Table C-7 FEPs Less Relevant for Near-Surface Disposal of LLW in the United States

Excluded FEP	ISAM ID	Rationale
Future human action assumptions[1]	0.05	The scope of this FEP is limited. Future societal and technology development will occur, but is difficult to predict. Therefore, unnecessary speculation about future human actions should be avoided. The uncertainty associated with future human actions is accounted for in the technical analyses by using reasonably conservative receptor scenarios.
Future human behavior (target group) assumptions[1]	0.06	The scope of this FEP is limited. Future human behavior is difficult to predict. Unnecessary speculation about future human behavior should be avoided.
Retrievability	1.1.13	LLW disposal facilities in the United States are not designed for retrievability.
Orogeny and related tectonic processes at plate boundaries	1.2.01	Orogeny and related tectonic processes at plate boundaries are only expected to be important for near-surface disposal facilities if very long performance periods are evaluated.
Anorogenic and within-plate tectonic processes (Deformation, elastic, plastic, and brittle)	1.2.02	Anorogenic and within-plate tectonic processes are only expected to be important for near-surface disposal facilities if very long performance periods are evaluated.
Metamorphism	1.2.05	Metamorphism is not expected to be important for near-surface disposal facilities or in the timeframes of interest.
Diagenesis[2]	1.2.08	Diagenesis is not expected to be important for near-surface disposal facilities or in the timeframes of interest.
Human influences on climate including ozone depletion, global warming, and greenhouse effect.	1.4.01	Future anthropogenic impacts on climate change are difficult to predict and are covered under natural climate change.
Motivation and knowledge issues (inadvertent/deliberate human actions)	1.4.02	The scope of this FEP is limited. Advertent intruders are not protected under 10 CFR Part 61.

Table C-7 FEPs Less Relevant for Near-Surface Disposal of LLW in the United States

Excluded FEP	ISAM ID	Rationale
Pollution (as it impacts site performance, radionuclide mobility, or monitoring)	1.4.07	The scope of this FEP is limited. Unnecessary speculation about future pollution should be avoided. Current and reasonably foreseeable pollution should be considered.
Social and institutional developments	1.4.11	The scope of this FEP is limited. Unnecessary speculation regarding future human actions and behavior should be avoided such as changes in demography, land use, controls, and regulatory requirements that may not need to be evaluated. Loss of control of a site due to loss of records or societal memory should be included and is considered in the inadvertent intruder analysis.
Technological developments	1.4.12	The scope of this FEP is limited. Technological developments are likely to occur but difficult to predict. Unnecessary speculation regarding future technological advances should be avoided (e.g., cure for cancer, technological advances in food production).
Explosions and crashes	1.4.14	The scope of this FEP is limited. For example, deliberate or malicious human actions may not need to be considered.
Meteorite impact[3]	1.5.1	Considered unlikely.
Species evolution[3]	1.5.2	Expected to be of limited significance in the timeframes of interest and with unknown impact.
Miscellaneous and FEPs of uncertain relevance[3]	1.5.3	Items in this category are not considered likely or significant to near-surface, LLW disposal (e.g., extraterrestrial activity, dust, changes in magnetic field, change in tidal processes).
Non-radiological toxicity/effects	3.3.08	Non-radiological effects are not considered.

[1] FEP of limited scope.
[2] Table C-9 includes a portion of this FEP (pedogenesis) that may need to be considered.
[3] NEA FEPs that are excluded from the ISAM FEPs list.

Table C-8 Assessment Context, Site Characterization, or Operational Factors Considered in Developing FEPs

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example Factors (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
Assessment endpoints (including intermediate outputs or results)	0.01		Points of assessment (e.g., well location, horizontal distance from source) (SRS 5.3.18)
			Annual Individual Dose (BMA 2.1.2., 2.1.2.1., BMO 1.1.2.1., HAN 0.4.06.01)
			Radionuclide Flux or Concentration (BMO 1.1.2.8, BMA, 2.1.2.8., SRS 1.1.09, SRS 5.3.12, HAN 0.4.06.08, HAN 0.4.06.09, HAN 0.4.06.10)
			Results, Presentation of (e.g., multiple lines of reason, barrier analysis, documentation, use of simpler models) (HAN 0.4.08)
Timescales of concern	0.02		Timeframes (BMA 2.1.7)
			Post-closure period (HAN 0.2.02.03)
			Assessment Timeframe (e.g., institutional control period, compliance period, >10,000 years, peak impact) (HAN 0.4.01, SRS 1.1.06, CLV 2)
			Safety Effects Beyond Periods of Control (beyond institutional control period) (SRS 1.1.07)
Spatial domain of concern[8])	0.03		Assessment Domain/Spatial Domain of Concern (HAN 0.4.02, SRS 1.1.08, CLV 4)
Facility[9] assumptions (e.g., assumptions regarding the success of facility closure and any changes to design, construction, or waste emplacement)	0.04		Repository System (BMA 2.1.4)
			Site, Context (BMA, 2.1.5, BMO 1.1.4)
			Facility Type (BMO 1.1.3)
			Disposal Facility Assumptions (HAN 0.4.09)
			Facility Factors (life cycle of disposal facility) (SRS 3.1.03)
Dose response assumptions[10]	0.07		Dose Response Assumptions (HAN 0.4.07)
Assessment purpose	0.08		Assessment Purpose (e.g., site selection and characterization, design, compliance, WAC, corrective action, confidence) (BMA 2.1.1, BMO 1.1.1, HAN 0.1, SRS 1.1.02)

[8] Spatial extent over which disposed waste presents a risk to human health.
[9] The ISAM FEP name was changed from "repository assumptions" to "facility assumptions" to avoid confusion related to terminology.
[10] For example, linear relationship of human health effect to dose with no threshold dose below which no effects are observed.

Table C-8 Assessment Context, Site Characterization, or Operational Factors Considered in Developing FEPs

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example Factors (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Assessment Audience (HAN 0.4.05)
Regulatory requirements and exclusions	0.09		Regulatory Requirements and Criteria (e.g., radiological protection standards, optimization) (HAN 0.2, CLV 3)
			Protection of Human Health and the Environment (SRS 1.2.02)
			Performance Requirements and Criteria (SRS 1.2.03)
			ALARA (SRS 1.2.05)
			Functional and Technical Requirements (e.g., containment, isolation, characterization, design, construction, quality assurance (QA), waste acceptance criteria (WAC), monitoring, analog, peer review) (HAN 0.2.03, SRS 1.2.04)
			Waste Acceptance Criteria (SRS 1.2.07)
Model and data issues (e.g., uncertainty, model abstraction)	0.10		Uncertainties, or confidence (BMA, 2.1.2.10)
			Confidence, Model (e.g., calibration, verification, validation) (HAN 0.3.04, SRS 1.3.12)
			Uncertainties, treatment of (e.g., subjective, future, conceptual, mathematical, model, parameter) (HAN 0.3.02, SRS 1.3.10)
			Sensitivity Analysis, Performance of (HAN 0.3.03, SRS 1.3.11)
			Model and Data Issues (including conceptual and mathematical model uncertainty, discretization, boundary conditions, coupled processes; parameter development and correlations; and scale issues) (SRS 1.3.01, CLV 1)
			Software Codes (SRS 1.3.02)
Assessment Philosophy or Approach	New		Assessment Philosophy (e.g., assessment and modeling approach, treatment of uncertainty, sensitivity analysis, and confidence building) (BMA 2.1.3, HAN 0.3)
			Assessment Approach (e.g., iterative, systemic, realistic, conservative, transparent) (HAN 0.3.01, SRS 1.3.04, SRS 1.3.05, SRS 1.3.06, SRS 1.3.07, SRS 1.3.08, SRS 1.3.09)
			Modeling Approach (e.g., screening, bounding, deterministic, probabilistic) (HAN 0.3.05, SRS 1.3.03)
			Alternative Simplified Modeling Approach (SRS 1.3.13)

Table C-8 Assessment Context, Site Characterization, or Operational Factors Considered in Developing FEPs

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example Factors (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Transparency of Assessment Approach (SRS 1.1.05)
			Documentation and Presentation of Results (SRS 1.1.04)
Site investigation	1.1.01		Technical Requirements (e.g., site characterization) (HAN 0.2.03)
			Investigations, Site (e.g., geology, hydrogeology, geochemistry, tectonic and seismicity, surface environment, meteorology and climatology, geography and demography, natural resources and land use) (HAN 1.1.01, CLV 82)
			Site Characterization and Investigations (SRS 3.1.01)
Schedule and planning	1.1.09		Schedule and Planning (e.g., construction, operation, and closure scope and schedule; alternative schedule) (HAN 1.1.03, SRS 3.2.02)
Administrative control, facility site[11]	1.1.10		Administrative control, Disposal facility (from pre- to post-closure and failures) (HAN 1.1.08, SRS 1.2.06)
			Institutional control (CLV 71)
Monitoring of facility[12]	1.1.11		Operation, Disposal Facility (e.g., monitoring) (HAN 1.1.05, CLV 84)
			Radionuclide Fluxes to the Biosphere (to monitor barrier performance) (SRS 5.3.12)
			Releases Prior to Closure (SRS 6.4.01)

[11] The ISAM FEP name was changed from "repository assumptions" to "facility assumptions" to avoid confusion related to terminology.
[12] The ISAM FEP name was changed from "repository assumptions" to "facility assumptions" to avoid confusion related to terminology.

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
Design, facility[13]	1.1.02		Design, Disposal Facility (e.g., description, documentation, functional requirements, features, alternative designs) (HAN 1.1.02, CLV 101)
			Design error (CLV 123)
Construction, facility[14]	1.1.03		Construction, Disposal Facility (e.g., process, performance and verification, alternative conditions) (HAN 1.1.04)
			Construction (includes factors related to the excavation, stabilization, and the installation and assembly of structural elements) (SRS 3.2.05)
			Material defects (CLV 124)
Emplacement of wastes and backfilling	1.1.04		Operation, Disposal Facility (e.g., waste emplacement and repackaging; backfill preparation; handling and emplacement) (HAN 1.1.05)
			Operation (waste emplacement, backfilling, monitoring and surveillance, remedial activities) (SRS 3.2.06)
			Void Space Formation (SRS 3.8.06)
			Waste Type Classification (as it impacts disposal requirements for different classes of waste) (SRS 4.1.01)
			Waste Form Characteristics (SRS 4.1.02)
			Waste allocation and emplacement (SRS 4.1.04)
			Localized Interactions Between Emplaced Wastes (SRS 4.2.05)
Closure, facility[15]	1.1.05		Closure, Disposal Facility (e.g., closure plan, performance requirements, failure mechanisms, construction, confirmation, remedial alternatives) (HAN 1.1.06)
			Disposal Unit and/or Facility Closure (includes activities undertaken to prevent human access into and limit the migration of contaminants from the individual waste tanks) (SRS 3.2.08)

[13] The ISAM FEP name was changed from "repository assumptions" to "facility assumptions" to avoid confusion related to terminology.
[14] The ISAM FEP name was changed from "repository assumptions" to "facility assumptions" to avoid confusion related to terminology.
[15] The ISAM FEP name was changed from "repository assumptions" to "facility assumptions" to avoid confusion related to terminology.

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Closure System Features and Materials (SRS 3.3.01)
			Compaction Error (CLV 98)
Waste allocation (projected inventory, waste acceptance criteria)	1.1.07		Operation, Disposal Facility (e.g., waste acceptance, waste allocation) (HAN 1.1.05)
			Radionuclide inventory disposed and remaining in the disposal facility (HAN 0.4.6.11)
			Activity limits in disposed waste (HAN 0.4.6.12, SRS 4.2.02)
			Waste allocation and emplacement (SRS 4.1.04)
			Homogeneity (SRS 4.1.05)
			Waste Acceptance Criteria (SRS 1.2.07)
Quality control	1.1.08		Quality control (CLV 88)
			Technical Requirements (e.g., QA) (HAN 0.2.03)
			Quality Assurance (e.g., all stages including research and development, procurement, manufacturing, siting, design, construction, commissioning, operation, decommissioning, QA/QC failures) (HAN 1.1.07)
			Procurement of Items and Services (quality assurance) (SRS 3.2.03)
			Manufacturing and Commissioning of Components (including defects) (SRS 3.3.02)
			Inadequate Quality Assurance/Control and Deviations from Design (SRS 3.8.04)
Accidents and unplanned events[16]	1.1.12		Accidents and unplanned events (e.g., human-induced and naturally occurring) (HAN 1.1.09, SRS 6.4.05, CLV 99, CLV 91)
Seismicity	1.2.03		Seismicity and effects (e.g., soil liquefaction) (HAN 1.2.03, SRS 6.2.01, CLV 50)
			Seismicity Associated with Igneous Activity (SRS 6.2.04)
			Earthquakes (CLV 40)
			Tsunami (CLV 30)

[16] For example, earlier than expected engineered barrier system failure, unexpected event, or unexpected waste.

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Faulting (CLV 41)
Volcanic and magmatic activity	1.2.04	Long-term	Volcanic and magmatic activity (HAN 1.2.04, SRS 6.3.02, CLV 52)
			Igneous Intrusion Into the Closure Facility (SRS 6.3.01)
			Geological intrusion (CLV 43)
Hydrothermal activity	1.2.06	Long-term	Hydrothermal activity (HAN 1.2.06, SRS 5.2.02, CLV 13)
Erosion and sedimentation	1.2.07		Denudation and Deposition (large-scale, including erosion, corrasion, weathering, fluvial, aeolian, glacier, coastal, mass-wasting, sedimentation, deposition, events triggering mass wasting) (HAN 1.2.07, CLV 10, CLV 11)
			Geomorphologic response to geological changes (e.g, structural, weathering, erosional, and depositional landforms) (HAN 1.2.13, CLV 13)
			Depositional Environments and Landforms (including beaches, deltas, flood plains, and glacial moraines) (SRS 2.5.03)
			Sedimentation (SRS 2.6.06, CLV 14)
Pedogenesis[17]	1.2.08		Pedogenesis (factors related to the development and origin of soils, may also effect caps) (HAN 1.2.09, SRS 2.6.05, CLV 59)
Salt diapirism and dissolution	1.2.09	Long-term	Salt diapirism and dissolution (intrusion or upwelling of a salt formation into overlying strata (such as salt domes). Salt dissolution can occur when any soluble mineral is removed by flowing water) (HAN 1.2.10, SRS 2.6.11, CLV 9, CLV 38)
Hydrological/ hydrogeological response to geological changes	1.2.10	Long-term	Hydrological/hydrogeological response to geological changes (e.g., change in boundary conditions, surface water flow path, geochemical properties, and hydraulic properties; and preferential pathways) (HAN 1.2.12, SRS 5.2.01, CLV 13, CLV 120)
			Unconsolidated soft zones (as it affects site stability and contaminant flow and transport) (SRS 2.5.07)

[17] Diagenesis was originally included with this FEP; however, diagenesis is excluded in Table C-6.

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

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Climate change, global[18]	1.3.01	Long-term	Description of Climate Change (BMA 2.2.1.1, BMO 1.3.1.2)
			Climate-driven changes (BMO 2.1.1.2)
			Climate change, global (e.g., climate reconstruction, climate change theories) (HAN 1.3.01, SRS 2.7.07, CLV 31)
			Isostatic effects (CLV 46)
Climate change, regional and local	1.3.02		Description of Climate Change (BMA 2.2.1.1, BMO 1.3.1.2, SRS 2.7.02)
			Climate-driven changes (BMO 2.1.1.2)
			Climate change, regional and local (e.g., climate fluctuations, volcanic eruptions, global climate induced changes, lake effects) (HAN 1.3.02, SRS 2.7.07, CLV 31, CLV 32)
Sea level change	1.3.03	Long-term	Sea level changes (HAN 1.3.03)
			Isostatic Effects (CLV 46)
Periglacial effects (physical processes in cold but ice sheet free environments)	1.3.04	Long-term	Cold weather effects (permafrost, freeze/thaw cycles, frost heaving, gelifluction) (SRS 2.7.06, CLV 35)
			Periglacial (HAN 1.3.04, CLV 34)
			Solifluction (CLV 12)
			Glacial and ice sheet effects, local (HAN 1.3.05, CLV 34)
Glacial and ice sheet effects, local	1.3.05	Long-term	Warm climate effects (HAN 1.3.06, SRS 2.7.05)
Warm climate effects (tropical and desert)[19]	1.3.06		Hydrological/hydrogeological response to climate changes (e.g., change in driving forces of flow and flow) (HAN 1.3.07)
Hydrological/ hydrogeological response	1.3.07	Long-term	Climate Driven Changes (BMO 2.1.1.2)

[18] Does not include anthropogenic impacts on climate change.
[19] Facilities in tropical climates may experience extreme weather patterns such as monsoons, hurricanes, flooding, storm surges, high winds etc.; arid climates may be dominated by infrequent storm events.

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

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to climate changes			Ecological changes (BMA 2.3.1.1.3, CLV 57)
Ecological response to climate changes	1.3.08		Climate Driven Changes (BMO 2.1.1.2)
			Ecological response to climate changes (e.g., soil, water, atmosphere, solar radiation, living organisms, ecological adaptation) (HAN 1.3.08, CLV 28)
Other geomorphological changes	1.3.10		Geomorphologic responds to climate changes (e.g., periglacial landforms, warm climate) (HAN 1.3.10)
			Surface excavations (e.g., construction, remediation, geotechnical investigation, waste disposal) (HAN 1.4.07, CLV 65)
Pollution (as it impacts site performance, radionuclide mobility, or monitoring)[20]	1.4.07		Artificial soil fertilization (BMA 2.3.2.1.1, BMO 2.2.3.3)
			Chemical pollution (BMA 2.3.2.1.2, BMO 2.2.1.1)
			Acid rain (BMA 2.3.2.1.3, BMO 2.2.1.1.1, SRS 2.7.04)
			Pollution (e.g., soil, groundwater, and air that may increase mobility of radionuclides) (HAN 1.4.12, SRS 2.2.07)
Inventory, radionuclide and other material	2.1.01		Inventory, waste (e.g., waste stream, volume, homogeneity, radiological content, non-radiological content (as it impacts radionuclide mobility), classification, uncertainty) (HAN 2.1.01, SRS 4.1.03)
			Source Term/Radionuclide Content (BMA 2.1.6, BMO 1.2.3.1)
Wasteform materials, characteristics and degradation processes	2.1.02		Wasteform, characteristics and degradation processes (HAN 2.1.02, CLV 100)
			Removal or Stabilization of Waste (stabilization of waste) (SRS 3.2.07)
			Waste characteristics (e.g., metallic, inorganic/non-metallic, organic, volatile, combustible) (SRS 4.1.07, 4.1.08, 4.1.09, 4.1.10, CLV 77, CLV 104)
			Waste degradation (inorganic and organic) (SRS 4.2.06, SRS 4.2.07)
Container materials, characteristics and	2.1.03		Container materials, characteristics and degradation processes (e.g., corrosion) (HAN 2.1.03, CLV 96, CLV 97, CLV 100)

[20] Unnecessary speculation about future pollution should be avoided. Current and reasonably foreseeable pollution should be considered.

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degradation processes			Waste tank, container, or package characteristics (physical, chemical and mechanical properties) (SRS 3.3.04)
			Waste Container, Package, or Over-Pack Failure (e.g., corrosion, manufacturing defects, improper seal) (SRS 3.7.06)
Buffer/backfill materials, characteristics and degradation processes	2.1.04		Buffer/backfill, characteristics and degradation processes (HAN 2.1.04, CLV 100)
			Closure System Buffer (Closure Cap, Backfill, and Near-Field Soil) Properties (e.g., dehydration of zeolites, mineralogical dehydration, geothermal fluid impacts, sorption, use of bentonite and vermiculite) (SRS 3.3.05, SRS 3.3.06)
			Swelling of Backfill and Emplacement Materials (e.g., bentonite and vermiculite degradation) (SRS 3.3.06, SRS 3.7.08)
Engineered barriers system (EBS), characteristics and degradation processes	2.1.05		Other engineered features, characteristics and degradation processes (e.g., final or interim covers or multi-layer cap designs) (HAN 2.1.05, CLV 100)
			Multi-Barrier Safety Function (combination of natural and engineered barriers) (SRS 3.1.04)
			Design Basis for Engineered Components (SRS 3.2.01)
			Consolidation of System Components (consolidation of engineered barrier system components that may affect the chemical environment and release) (SRS 3.3.03)
			Chemical Degradation of Engineered System Metals (SRS 3.7.01)
			Corrosion (e.g., stress corrosion cracking, hydride cracking) (SRS 3.7.02, SRS 3.7.03)
			Creep of Metallic Materials in the Engineered System (SRS 3.7.04)
			Oxygen Embrittlement of Engineered System Metals (SRS 3.7.05)
			Concrete Shrinkage/Expansion (may impact hydraulic properties) (SRS 3.7.09)
			Cementitious material degradataion (e.g., sulfate and chloride attack, carbonation, (SRS 3.7.10, SRS 3.7.11)
			Seismic-Induced Damage or Changes to System Components (SRS 6.2.02)
			Frost Weathering (engineered cover degradation mechanism) (CLV 21)
			Geophysical effects on degradation (CLV 36)

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Other engineered features materials, characteristics and degradation processes	2.1.06		Other engineered features, characteristics and degradation processes (e.g., vault structure, site cut off walls or fire breaks, engineered drainage system) HAN 2.1.05
			Engineered Barrier Thickness and Other Material Properties (e.g., closure cap, vaults, basemat) (SRS 3.3.07, SRS 3.3.08, SRS 3.3.09, CLV 100)
			Ancillary Equipment and Piping/Transfer Lines (SRS 3.3.10)
			Degradation of Non-Metal Solids: Backfill, Rock, Grout, Cement, etc. (SRS 3.7.07)
			Polymer Degradation (SRS 3.7.12)
			Material Volume Changes (e.g., expansion may lead to cracking of materials) (SRS 3.8.07)
Mechanical processes and conditions (in wastes and EBS)	2.1.07		Mechanical Effects at EBS Component Interfaces (e.g., mechanical and static loading) (SRS 3.8.09)
			Effects of Subsidence (including increased infiltration) (SRS 6.2.03, CLV 8, CLV 103)
			Cave-In, Collapse, or Rockfall (SRS 6.4.04)
			Compaction Error (CLV 98)
Hydraulic/hydrogeological processes and conditions (in wastes and EBS)	2.1.08		Hydrological Processes and Conditions (processes affecting flow through waste and engineered features) (SRS 3.4.01, CLV 99)
			Hydrostatic Pressure on the Closure System (hydrostatic pressure (or suction) of saturated waste and engineered system components) (SRS 3.4.02)
			Condensation on Closure System Surfaces (SRS 3.4.03)
			Resaturation and Desaturation (equilibration of engineered barriers with surrounding materials, may cause hydraulic, thermal, chemical, mechanical changes such as expansion, cooling, corrosion) (SRS 3.4.04)
			Groundwater Flow and Movement (Near-Field) (e.g., preferential flow) (SRS 5.1.01)
			Focusing of Flow Along Preferred Flow Paths (Fingers, Weeps, Faults, Fractures, etc.) (SRS 5.1.05)
			Episodic Or Pulse Flow and Release (SRS 5.1.03)
			Water Influx at the Closure Facility (SRS 5.1.04)

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			Flow Diversion and Bypass Flow (focused flow around cap, flow through voids such as roots) (SRS 5.1.07)
			Film/Laminar Flow (through waste zone) (SRS 5.1.08)
			Perched Water (SRS 5.2.06)
			Contaminant Release Pathways (SRS 5.3.02, CLV 102)
			Multi-Phase Transport Processes (SRS 5.3.03)
			Fast Transport/Preferential Pathways (SRS 5.3.13, CLV 120)
			Flooding or drainage system failure (SRS 6.4.02)
			Mechanical effects (CLV 125)
Chemical/geochemical processes and conditions (in wastes and EBS)	2.1.09		Chemical/geochemical-mediated processes, effects on contaminant release and migration (including dissolution, precipitation, speciation, solubility, sorption/desorption, colloids, chemical complexing agents, and reconcentration; interface between near- and far-field; and effects on sorption and permeability) (HAN 3.2.02, SRS 3.5.01, SRS 5.3.01, CLV 9, CLV 102)
			Evolving water chemistry in wasteform, containment system, or near-field (e.g., dissolution of cementitious materials and impacts on contaminant mobility; impacts of leachate on near-field transport; pH and Eh changes; colloid generation) (SRS 3.5.02, SRS 3.5.03, SRS 3.5.05, SRS 3.5.06, SRS 3.5.07, CLV 9, CLV 102)
			Chemical Effects of Waste-Rock Contact (direct contact of waste with rock due to failure of waste package) (SRS 3.5.08)
			Rind (Chemically Altered Zone) Forms in the Near-Field (thermal-chemical processes involving precipitation, condensation, and re-dissolution could alter the properties of the adjacent materials) (SRS 3.5.09)
			Reaction Kinetics (non-equilibrium conditions) (SRS 3.5.11)
			Contaminant Release from the Waste Form and Engineered Barrier System (SRS 5.3.04, CLV 99)
			Long-Term Release of Radionuclides (SRS 5.3.14)
			Electrochemical effects (CLV 107)

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Biological/biochemical processes and conditions (in wastes and EBS)	2.1.10		Microbial/biological-mediated processes, effects on contaminant release and migration (e.g., biological activity that may change radionuclide mobility and microbes as colloids) (HAN 3.2.03, SRS 2.4.02, CLV 54, CLV 102)
Thermal processes and conditions (in wastes and EBS)	2.1.11		Thermal Processes and Conditions the Engineered System (as from cement hydration, radioactive decay) (SRS 3.6.01)
			Thermo-Chemical Alteration, Near-Field (e.g., effects on solubility) (SRS 3.6.03)
			Thermo-Mechanical Stresses Alter Characteristics of Engineered Barrier System Components (e.g., thermal cracking of cementitious materials) (SRS 3.6.04)
			Recrystallization of Vitrified Wastes (SRS 3.6.05)
Gas sources and effects (in wastes and EBS)	2.1.12		Waste Form Characteristics(e.g., gas generation) (HAN 2.1.02, SRS 4.1.02)
			Gas generation (e.g., radon) (CLV 58)
Radiation effects (in wastes and EBS) (e.g., radiolysis, material degradation)	2.1.13		Radiation Effects on the Waste Closure System (SRS 4.5.02)
			Radiolysis Effects (SRS 4.5.07)
			Radiological effects (CLV 55)
Nuclear criticality	2.1.14		Nuclear Criticality (HAN 1.1.11, SRS 4.5.01, CLV 105)
Extraneous materials	2.1.15		No examples were identified.
Disturbed zone, host lithology	2.2.01		Disturbed zone, host lithology (e.g., formation of cracks, interface, hydro mechanical effects, backfilling, contaminant migration) (HAN 2.2.03)
Host lithology	2.2.02		Host lithology (e.g., geological properties, physical characteristics) (HAN 2.2.02, CLV 119, CLV 100)
			Stratigraphy and Host Lithology (including description, flow and transport effects, properties, homogeneity, and potential changes) (SRS 2.5.04)
Lithological units, other	2.2.03		Stratigraphy (e.g., stratrigraphic record, formation) (HAN 2.2.01, CLV 119)
Discontinuities, large scale (in geosphere)	2.2.04		Discontinuities, large scale (in geosphere) (e.g., faults, folds, dykes, aquifer formation, discontinuities affecting boundary conditions) (HAN 2.2.04, SRS 2.5.05, CLV 39)
Contaminant transport path characteristics (in	2.2.05		Contaminant migration path characteristics (in geosphere) (e.g., hydrogeological zones, interstitial geometry, bypass flow, fracture infill, weathering) (HAN 2.2.05, CLV 111)

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geosphere) (e.g., fracture flow, porous flow, fracture/matrix interactions)			Unconsolidated soft zones (SRS 2.5.07)
			Fast Transport Pathways (SRS 5.3.13)
Mechanical processes and conditions (in geosphere)	2.2.06		Mechanical processes and conditions (in geosphere) (e.g., changes in stress field, mechanical load, mechanical rapture, changes in rock properties) (HAN 2.206, SRS 2.6.01)
			Stress Regimes (caused by coupled thermal-hydro-mechanical effects; swelling of materials; isostatic rebound (such as when glaciers recede), salt creep, etc., and can lead to changes in flow/directions). (SRS 2.5.09)
Hydraulic/hydrogeological processes and conditions (in geosphere)	2.2.07		Hydraulic/hydrogeological processes and conditions (in geosphere) (e.g., hydrological cycle, groundwater flow, saturated/unsaturated flow, water table fluctuations, boundary conditions/variability, gradients, hydraulic properties/variability, salinity, geothermal gradient) (HAN 2.2.07, SRS 2.5.11, SRS 2.6.12, SRS 5.1.02, SRS 5.1.09, SRS 5.2.03, CLV 16, CLV 100)
			Hydrological Regime and Water Balance (Near-Surface) (SRS 2.8.09)
			Aquifer Properties (including vadose and saturated zone thicknesses) (SRS 5.3.16, 5.3.17)
			Capillary rise (SRS 2.8.05)
			Discharge Zones Within and Outside the Assessment Domain (including discharge to sensitive or remote areas) (SRS 2.8.07, SRS 2.8.08, SRS 5.3.15)
			Interfaces Between Different Waters (SRS 5.2.04)
			Chemically-Induced Density Effects on Groundwater Flow (SRS 5.1.06)
			Unconsolidated soft zones (SRS 2.5.07)
			Hydrological Effects (CLV 17)
			Flooding (CLV 19)
Chemical/geochemical	2.2.08		Properties of the Groundwater Plume (BMO 1.2.3.2)

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processes and conditions (in geosphere)			Chemical/geochemical processes and conditions (in geosphere) (e.g., chemical composition and evolution; geochemistry factors, evolution and geochemical interactions; groundwater recharge; geothermal effects, solubility controls) (HAN 2.2.08, CLV 9)
			Evolving Water Chemistry in the Far-Field (e.g., perturbations due to climate change which can cause infiltration of sea-water or glacial melt waters) (SRS 3.5.04)
			Complexation in the Natural System (SRS 3.5.10)
			Alteration and Chemical Weathering Along Flow Paths (SRS 5.1.10)
Biological/biochemical processes and conditions (in geosphere)	2.2.09		Biological/biochemical processes and conditions (in geosphere) (e.g., biogeochemical changes, generation of chelating agents, microbial species, influence on pH and redox potential, and changes in microbial populations) (HAN 2.2.09, CLV 54)
Thermal processes and conditions (in geosphere)	2.2.10		Thermal processes and conditions (in geosphere) (e.g., sources and distribution of geothermal heat, geothermal gradient, temperature, and geothermal induced changes from fracturing, fracture displacement, solubility changes, or changes in flow directions due to buoyancy) (HAN 2.2.10, SRS 3.6.02)
			Temperature and Thermal Gradient Effects on the Geosphere (temperature can influence rates of chemical and microbiological processes, stress field, groundwater flow, diffusion rates, and radionuclide transport) (SRS 3.6.07)
Gas sources and effects (in geosphere)	2.2.11		Gas sources and effects (in geosphere) (e.g., effects of natural gases, gas induced groundwater flow) (HAN 2.2.11)
			Gas or brine pockets (CLV 6)
Undetected features (in geosphere) (e.g., boreholes, abandoned mines, gas or brine pockets, geological features [faults, dykes, lava tubes, breccia pipes, lava tubes])	2.2.12		Undetected features (in geosphere) (HAN 1.2.11, SRS 2.5.08)
			Breccia pipes (CLV 37)
			Lava tubes (CLV 47)
			Gas intrusion (CLV 121)

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Geological resources	2.2.13		Geological resources (in geosphere) (e.g., methane, water, and other resources; and near-surface and deep deposit exploration) (HAN 2.2.12, CLV 119)
			Natural and Geological Resources and Land Use (resources including water, lumber, oil, gas, minerals, geothermal energy; land use including reclamation, logging, agricultural, urbanization, and waste disposal) (SRS 2.2.01, CLV 79)
			Hydraulic fracturing (CLV 44)
			Resource extraction (CLV 89)
Topography and morphology	2.3.01		Topography and morphology (e.g., landform, changes in landform, topography changes on climate) (HAN 2.3.01, SRS 2.5.02)
Soil and sediment (physical, chemical and biological properties; sedimentation; evolution)	2.3.02		Chemical changes (e.g., chemical changes to soil) (BMA 2.3.1.1.2)
			Geosphere/Biosphere Interface (e.g., deep soil) (BMO 1.2.1)
			Environmental Components (e.g., top soil, deep soil) (BMO 1.3.2.3)
			Alkalinization (BMO 2.1.1.1.2.1)
			Soil conversion (BMO 2.1.1.1.3.1)
			Soil and sediment (composition, structure, profile, type, depth, and impact on contaminant mobility) (HAN 2.3.03, SRS 2.5.10)
			Radionuclide Accumulation (Recycling) in Soils (SRS 4.3.05)
			Sedimentation (CVL 14)
Aquifers and water-bearing features, near surface	2.3.03		Environmental Components (e.g., deep soil, biosphere aquifer) (BMO 1.3.2.3)
			Aquifers and water-bearing features, near surface (including water table depth, aquifer type, geometry [fractures], recharge and discharge zones, alkali flats, sea water intrusion) (HAN 2.3.04, SRS 2.5.06)
Lakes, rivers, streams and springs	2.3.04		Geosphere/Biosphere Interface (e.g., river) (BMO 1.2.1)
			Environmental Components (e.g., river water, river sediment) (BMO 1.3.2.3)

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			Terrestrial surface water bodies (lakes, dams, rivers, streams, springs, wetlands, dilution, and recharge/discharge zones) (HAN 2.3.05)
			Surface water bodies (characteristics of surface-water bodies such as rivers, lakes, wetlands and springs, and their evolution in time) (SRS 2.8.02, CLV 20)
			Lake Effects (including appearance, disappearance of large lake leading to possible sedimentation, wave action, erosion/inundation, isostasy) (CLV 18, CLV 32)
			Wave Action (from large lake) (CLV 33)
			Regional subsidence (effect on lake levels) (CLV 49)
Coastal features	2.3.05		Coastal features and processes (HAN 2.3.06, CLV 26)
Marine features	2.3.06		Marine features and effects (HAN 2.3.07, CLV 29)
Atmosphere (e.g., physical transport of gases, chemical and photochemical reactions, aerosols and dust)	2.3.07		Environmental Components (e.g., atmosphere) (BMO 1.3.2.3)
			Atmosphere (transport of contaminants in gas, vapor, or particulate/aerosol phase; contamination of atmosphere may occur due to water evaporation, degassing from soils or water, transpiration from plants, suspension due to wind erosion, plowing, or fires) (HAN 2.3.08, SRS 2.7.01)
			Effects related to air and vapor flow and evaporation within the system (SRS 5.2.05)
			Gas Transport (CLV 117)
			Resuspension (CLV 23)
			Atmospheric dispersion (CLV 24)
			Tornado (CLV 25)
Vegetation	2.3.08		Vegetation (including such factors as vegetation type, contamination processes, retention, fires, root intrusion, evolution, and hydroponics) (HAN 2.3.09, SRS 2.4.03, CLV 56)
Animal populations (e.g., diets, external contamination of)	2.3.09		Living components of ecosystems (BMA 2.2.3.2.1)
			Animal populations (including animal types, burrowing animals, scavengers and predators, and pets) (HAN 2.3.10, SRS 2.4.04)

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Meteorology	2.3.10		Identification and Characterization of Climate Categories (BMA 2.2.1.2)
			Differentiation of Climate Categories (BMO 1.3.1.1)
			Diurnal variability (BMA 2.3.1.2.1)
			Meteorology (HAN 2.3.11, CLV 22)
			Precipitation (control on the amount of runoff and infiltration, flow in the unsaturated zone, and groundwater recharge) (SRS 2.7.03)
			Events (e.g., flooding, tornados, hurricanes) (CLV 10, CLV 25, CLV 27)
			Insolation (CLV 28)
Hydrological regime and water balance (near surface)	2.3.11		Interannual and longer timescale variability (e.g., seasonal water table fluctuations) (BMA 2.3.1.2.3)
			Hydrological regime and water balance (near-surface) (HAN 2.3.12)
			Water (characteristics of water and its evolution) (SRS 2.8.01)
			Evapotranspiration, Surface Runoff, Infiltration and recharge (SRS 2.8.03, SRS 2.8.04, SRS 2.8.06, CLV 118)
			Hydrological Effects (CLV 17)
Erosion and deposition	2.3.12		Physical changes (e.g., erosion, sea level change) (BMA 2.3.1.1.1, BMO 2.1.1.1.3)
			Erosion (BMA 2.3.1.4.2.10, BMO 2.1.1.1.3.2, CLV 11)
			Erosion and deposition (HAN 2.3.13)
			Erosion and weathering (SRS 2.6.08)
			Deposition (SRS 2.6.07)
			Mass Wasting (soil movement as a result of gravitational forces) (SRS 2.6.09)
			Creeping of the Rock Mass (slow movement of the rock along pre-existing discontinuities or in the rock matrix due to differential stress fields; may affect hydraulic properties of the rock) (SRS 2.6.10)

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Subrosion (CLV 15)
Ecological/biological/microbial systems (e.g., features, microbial activity, chemical changes). The NEA database also has the following examples: fire, ecological succession.	2.3.13		Ecosystems (BMA 2.2.3.2)
			Non-living components of ecosystems (BMA 2.2.3.2.2)
			Interannual and longer timescale variability (e.g., natural succession after fire) (BMA 2.3.1.2.3)
			Burning (BMO 2.1.2.1.3)
			Chemical Changes Caused by Micro-Organisms (BMO 2.1.1.1.2.2)
			Ecological/biological/microbial systems (HAN 2.3.14)
			Biomes (e.g., desert, grassland, forest, and mountain biomes) (HAN 2.3.02, SRS 2.4.01)
			Insolation, effects of (CLV 28)
Animal/plant intrusion leading to vault/trench disruption (e.g., root uptake, burrowing animals)	2.3.14		Transport mediated by flora and fauna (e.g., root uptake, transpiration, interception, intake by fauna, bioturbation, burrowing, root development, translocation) (BMA 2.3.1.3.1, BMO 2.1.2.7, CLV 109)
			Animal/Plant intrusion (HAN 2.3.15, SRS 6.1.05)
Radioactive decay and in-growth	3.1.01		Radioactive decay and in-growth (HAN 3.1.01, SRS 4.2.01, CLV 60)
			Radionuclide properties, other (HAN 3.1.02)
Chemical/organic toxin stability	3.1.02		Chemical/organic toxin stability (HAN 3.1.04)
Inorganic solids/solutes	3.1.03		Inorganic solids/solutes (HAN 3.1.05)
Volatiles and potential for volatility	3.1.04		Volatiles and potential for volatility (HAN 3.1.06)
Organics and potential for organic forms	3.1.05		Organics and potential for organic forms (HAN 3.1.03)
Noble gases	3.1.06		Noble gases (HAN 3.1.07)
Dissolution, precipitation	3.2.01		Release Mechanisms (BMA 2,1.6.2, CLV 102)

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
and crystallisation, contaminant			Source Term Mechanisms (BMA 2.1.6.3)
			Dissolution/precipitation (BMA 2.3.1.4.4.1, BMO 2.1.3.1.1, SRS 4.3.02)
			Chemical/geochemical-mediated processes, effects on contaminant release and migration (e.g., dissolution, precipitation, and crystallisation) (HAN 3.2.02)
			Dissolution (CLV 115)
Speciation and solubility, contaminant	3.2.02		Source Term/Release Mechanisms (BMA 2,1.6.2, BMA 2.1.6.3, CLV 102)
			Chemical/geochemical-mediated processes, effects on contaminant release and migration (e.g., speciation and solubility) (HAN 3.2.02, CLV 9)
			Contaminant Solubility, Solubility Limits, and Speciation (SRS 4.2.03)
			Reduction-Oxidation Potential (Redox Fronts) (SRS 4.2.04)
			Solubility and Sorption Changes From Chemical and Temperature Interactions (SRS 4.3.03)
Sorption/desorption processes, contaminant	3.2.03		Source Term/Release Mechanisms (BMA 2,1.6.2, BMA 2.1.6.3, CLV 102)
			Adsorption/desorption (BMA 2.3.1.4.4.2, BMO 2.1.3.1.2, SRS 5.3.11, CLV 111)
			Soil and sediment (e.g., sorptive capability) (HAN 2.3.08)
			Chemical/geochemical-mediated processes, effects on contaminant release and migration (e.g., sorption/desorption processes) (HAN 3.2.02, CLV 9)
			Electrochemical Effects in the Closure System (Including Anion Exclusion) (SRS 3.8.08)
			Solubility and Sorption Changes From Chemical and Temperature Interactions (SRS 4.3.03)
			Radionuclide Interaction with Corrosion Products (SRS 4.5.03)
Colloids, contaminant interactions and transport with	3.2.04		Colloid formation (BMA 2.3.1.4.4.3)
			Transport of Colloids (BMO 2.1.2.3.6.2)
			Colloids mediated migration of contaminant (HAN 3.2.10, CLV 110)

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
Chemical/complexing agents, effects on contaminant speciation/transport	3.2.05		Source Term Content of Other Hazardous Materials[21] (BMO 1.2.3.3)
			Chemical/geochemical processes and conditions (in geosphere) (e.g., naturally occurring complexing agents or complexing agents formed in the near-field) (HAN 2.2.08, CLV 9)
			Chelating Agent Effects (SRS 3.5.12)
Microbial/biological/plant-mediated processes, contaminant	3.2.06		Microbial/biological-mediated processes, effects on contaminant release and migration (HAN 3.2.03, SRS 2.4.02, CLV 54, CLV 102)
Water-mediated transport of contaminants	3.2.07		Water-borne transport (e.g., surface run-off, infiltration, percolation, multi-phase flow, recharge, capillary rise, groundwater transport, discharge) (BMA 2.3.1.4.2)
			Geosphere Aquifer Discharge (BMO 1.2.2.1.1)
			Porous Media Aqueous Transport Processes (e.g., infiltration, percolation, matrix diffusion, diffusion/dispersion, dual flow systems, capillary rise, groundwater transport) (BMO 2.1.2.3, CLV 118)
			Physical Processes (e.g., rainfall, snowfall, evaporation, evapotranspiration) (BMO, 2.1.3.2)
			Surface Water Aqueous Transport Processes (e.g., surface water run-off, transport in water bodies) (BMO 2.1.2.2, CLV 17, CLV 111)
			Water-mediated migration of contaminants (including groundwater advection, dispersion, dilution, imbibition, diffusion, multi-phase, unsaturated flow; surface water transport; currents; and sea spray) (HAN 3.2.04, SRS 5.3.07, SRS 5.3.08, SRS 5.3.09, CLV 16, CLV 112, 113, 114)
			Dilution of Radionuclides in Groundwater (SRS 4.3.04)
			Contaminant Release Pathways (water-mediated release from infiltration, breach of engineered barriers or wasteform, and leaching) (HAN 3.2.01, CLV 118, CLV 119)
			Leaching (SRS 3.5.14)
Solid-mediated transport of contaminants	3.2.08		Solid-phase transport (e.g., landslides, rock fall, wash out, sedimentation, resuspension, rain splash) (BMA 2.3.1.4.3, BMO 2.1.2.5, CLV 7)

[21] This FEP is included to the extent that chemical constituents impact the mobility of radionuclides. Non-radiological impacts are not considered.

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Solid-mediated migration of contaminants (including from erosion, denudation, resuspension, sediment migration, saltation, wet deposition, and mass wasting) (HAN 3.2.05, CLV 10, CLV 11, CLV 12)
			Contaminant Release Pathways (e.g., solid-mediated release from intrusion, natural disruption, or animal action) (HAN 3.2.01, CLV 102)
			Solid-Mediated Migration of Contaminants (SRS 5.3.05)
Gas-mediated transport of contaminants	3.2.09		Gaseous Release (BMO 1.2.2.2)
			Gaseous Transport (BMO 2.1.2.1.1.)
			Gas-mediated migration of contaminants (including expelling groundwater, gas-phase transport, and multi-phase flow effects) (HAN 3.2.06)
			Contaminant Release Pathways (gas-mediated release from barometric pressure changes, controlled release of gas, and dissolution; gas release models, transport processes, biosphere entry points, and monitoring may also be discussed) (HAN 3.2.01, CLV 102)
			Gas-Mediated Migration of Contaminants (SRS 5.3.06)
Atmospheric transport of contaminants	3.2.10		Atmospheric transport (e.g., gas, aerosols, evaporation, wet/dry deposition) (BMA 2.3.1.4.1)
			Aerosol Transport (BMO 2.1.2.1.2)
			Wet Deposition (BMO 2.1.2.5.4.5)
			Atmospheric migration of contaminants (including convection, diffusion, turbulence, deposition, saltation, burning, showers and humidifiers) (HAN 3.2.07, CLV 111)
			Dust devils (CLV 116)
Animal, plant and microbe mediated transport of contaminants (e.g., microbial-enhanced contaminant transport)	3.2.11		Recycling of bulk solid materials (e.g., recycling materials for compost or mulch) (BMA 2.3.2.3.5, BMO 2.2.3)
			Fodder products (BMA 2.4.1.1.3)
			Animal, plant and microbe mediated migration of contaminants (including animal intrusion, external contamination, carcasses, root uptake, microbes, translocation, leaf deposition) (HAN 3.2.08, SRS 4.4.04, CLV 54, CLV 111)

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
Radiological toxicity/effects	3.3.06		Radiological toxicity/effects (somatic, genetic, stochastic, non-stochastic) (HAN 3.3.07)
Scope of FEP limited. See Table C-7 for more information on what scope can be excluded from the FEP.			
Additional FEPs not included in the NEA international FEPs database.			

Table C-10 Generic FEPs List for Near-Surface Disposal in the United States (FEPs related to human actions, exposure assumptions, etc.)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
Future human action assumptions	0.05		Future Human Action Assumptions (e.g., present day technology, past as reflection of future) (HAN 0.4.03, SRS 2.3.01, CLV 67)[22]
Future human behavior (target group) assumptions	0.06		Future Human Behavior (target group) Assumptions (HAN 0.4.04, CLV 67) [23]
			Human Behavior and Habits (Non-Diet Related) (SRS 2.1.03, CLV 131)
Records and markers, facility[24]	1.1.06		System of Records (HAN 0.2.03.09)
			Loss/degradation of societal memory (HAN 1.4.02.06)
			Loss of archives/records (HAN 1.4.02.07)
Natural climate cycling (e.g. glaciation)	1.3.09	Long-term	Human behavior response to climate changes (e.g., irrigation rates) (HAN 1.3.09)
Motivation and knowledge issues[25] (inadvertent human actions)	1.4.02		Motivation and knowledge issues (inadvertent intrusion) (HAN 1.4.03)
			Inadvertent Intrusion (SRS 6.1.01, CLV 69)
			Loss/degradation of societal memory (HAN 1.4.02.06)
			Loss of archives/records (HAN 1.4.02.07)
			Future Knowledge of the Facility (loss of records) (SRS 2.3.02)

[22] The Hanford FEP includes three sub-categories of future human actions that are explicitly excluded in Table C-7: (i) cure for cancer, (ii) malicious acts or acts of war, (iii) deliberate intrusion. If a cure for cancer is assumed, then future generations will not be protected at the same level as current generations. Additionally, credit cannot be given for an assumed future mitigative action to meet regulatory standards today. The regulations in 10 CFR Part 61 do not protect deliberate acts or advertent intrusion. In general, analysts should avoid unnecessary speculation about future human actions that tend to reduce potential dose impacts. See Table C-7 for additional details.

[23] Use of dose estimates for the average member of the critical group, or that group of individuals reasonably expected to receive the highest dose based on current or reasonably foreseeable (e.g., within the next 100 years) future practices, is an acceptable approach for technical analyses. This FEP should not include unsupported assumptions regarding future human species evolution or changes to radiosensitivity. See Table C-7 for additional details.

[24] The ISAM FEP name was changed from "repository assumptions" to "facility assumptions" to avoid confusion related to terminology.

[25] The original ISAM FEP (and Hanford FEP) was named "Motivation and knowledge issues (inadvertent/deliberate human actions)" but was renamed "Motivation and knowledge issues (inadvertent human actions)". This FEP does not include advertent or deliberate intrusion into the disposal facility. See Table C-6 for additional details regarding exclusion of deliberate or advertent intrusion.

Table C-10 Generic FEPs List for Near-Surface Disposal in the United States (FEPs related to human actions, exposure assumptions, etc.)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Igneous or Seismic Event Precedes Human Intrusion (making it difficult to recognize engineered wasteform) (SRS 6.1.06)
Drilling activities (human intrusion)	1.4.03		Water extraction by pumping (BMA 2.3.2.2.2, BMO 2.2.4.1)
			Water recharge by pumping (BMA 2.3.2.2.3)
Mining and other underground activities (human intrusion)	1.4.04		Drilling activities (e.g., exploration, studies, site characterization, exploitation, construction, water-supply well, reuse of boreholes, waste disposal, remedial action, injection wells, geothermal) (HAN 1.4.04, SRS 6.1.03, CLV 73, CLV 80)
			Mining and other underground activities (e.g., mining, underground construction/dwelling, exploitation, exploration, excavation, solution mining, waste disposal, underground nuclear testing) (HAN 1.4.05, SRS 6.1.04, CLV 65, CLV 73, CLV 85)
Un-intrusive site investigation	1.4.05		Un-intrusive site investigation (HAN 1.4.06)
Surface excavations	1.4.06		Dredging (BMA 2.3.2.3.7, BMO 2.2.4.4.1)
			Ploughing (BMA 2.3.2.3.1, BMO 2.2.3.1)
			Earth Works (BMO 2.2.4.4.2)
Site Development	1.4.08		Land reclamation (BMA 2.3.2.2.5, BMO 2.2.2.3)
			Dam building (BMA 2.3.2.2.4, BMO 2.2.2.2)
			Construction (BMA 2.3.2.2.1)
			Site Development (e.g., construction, road building, dam building, drainage, change in topography, change in land use) (HAN 1.4.08, SRS 3.1.02)
			Community development (e.g., establishment of residences) (CLV 64, CLV 70)
			Land use (CLV 72)
Archaeology	1.4.09		Archaeology (HAN 1.4.09)
Water management	1.4.10		Well supply (BMA 2.3.2.3.2, BMO 2.2.4.1.1)

Table C-10 Generic FEPs List for Near-Surface Disposal in the United States (FEPs related to human actions, exposure assumptions, etc.)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
(wells, reservoirs, dams)			Dam building (BMA 2.3.2.2.4)
			Other water supply (BMA 2.3.2.3.3)
			Irrigation (BMA 2.3.2.3.4, BMO 2.2.3.1.2, CLV 83)
			Geosphere/Biosphere Interface (e.g., biosphere aquifer with well) (BMO 1.2.1)
			Environmental Components (e.g., well) (BMO 1.3.2.3)
			Water management (including construction of dams, reservoirs, canals, pipelines; and potential for flooding) (HAN 1.4.10, SRS 2.2.02, CLV 94)
			Flooding or drainage system failure (SRS 6.4.02)
Social and institutional developments[26]	1.4.11		Loss/degradation of societal memory (HAN 1.4.02.06)
			Loss of archives/records (HAN 1.4.02.07)
			Social and Institutional Developments (loss of records or society memory) (SRS 2.3.03)
Technological developments[27]	1.4.12		Technological development assumptions (e.g., including retrograde developments and no technological development) (HAN 1.4.14, SRS 2.3.04, SRS 2.3.05)
Remedial actions	1.4.13		Remedial actions (e.g., remediation, additional engineered barrier construction, waste retrieval) (HAN 1.4.13, SRS 3.8.05)
Explosions and crashes[28]	1.4.14	Long-term	Explosions and crashes (e.g., accidental human actions) (HAN 1.4.11, SRS 6.4.06, CLV 66, CLV 108)
Scope of FEP is limited. See Table C-7 for more information on what scope can be excluded from the FEP.			

[26] This FEP is limited in scope to include loss of records and societal memory. Other social and institutional developments may be excluded as they are difficult to predict. See Table C-7 for additional details.
[27] Several aspects of this FEP are excluded from consideration as they are difficult to predict and may be considered speculative such as a cure for cancer. See Table C-7 for additional details.
[28] Acts of war, terrorism, and sabotage may be excluded.

REFERENCES

BIOMOVS, 1996. BIOMOVS II, Technical Report 6, *Development of a Reference Biospheres Methodology for Radioactive Waste Disposal*, Final Report of the Reference Biospheres Working Group of the BIOMOVS II Study, September 1996.

Arlt, 2013. Arlt, Hans, "Note to File: Hanford Site Waste Management Area C Features, Events, and Processes List," March 8, 2013, ADAMS Accession No. ML13066A730.

IAEA, 2003. International Atomic Energy Agency, "Reference Biospheres for Solid Radioactive Waste Disposal: Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme," BIOMASS, IAEA-BIOMASS-6, Vienna, July 2003.

Neptune, 2011. Neptune and Company, Inc., *FEP Analysis for Disposal of Depleted Uranium at the Clive Facility,* May 2011.

NEA, 2000. Nuclear Energy Agengy, *Features, Events, and Processes (FEPs) for Geologic Disposal of Radioactive Waste*, *An International Database*, Radioactive Waste Management, OECD (Organisation for Economic Co-operation and Development), AEN NEA, 2000.

NEA, 2006. Nuclear Energy Agengy, *The NEA International FEP Database : Version 2.1 User Notes*, Nuclear Energy Agency, Safety Assessment Management Ltd., http://www.oecd-nea.org/rwm/igsc_coprojectactivities.html, 2006.

SRS, 2012a. U.S. Department of Energy Savannah River Site, *Features, Events, and Processes for Liquid Waste Performance Assessments*, SRR-CWDA-2012-00011, Rev. 0, February 2012.

SRS, 2012b. U.S. Department of Energy Savannah River Site, *Evaluation of Features, Events, and Processes in the F-Area Tank Farm Performance Assessment*, SRR-CWDA-2012-00022, Rev. 0, February 2012.

APPENDIX D
ADDITIONAL APPROACHES TO CONSTRUCT SCENARIOS AND CONCEPTUAL MODELS

This appendix presents techniques for constructing scenarios and conceptual models. Many of the techniques discussed may be from non-LLW examples (NEA, 1992; IAEA, 2004; NRC, 1995; SKB, 2008); however, the NRC staff believes the techniques and associated references could be of value to a licensee who is looking for possible approaches to construct alternative scenarios and alternate conceptual models. Licensees have the flexibility to use any documentable technique and are not required to use the techniques presented in this appendix.

The techniques presented here can provide a logical structure for the comprehensive documentation of the relevant processes and their representation in models or scenarios. The techniques are not mutually exclusive and may be used in combination. Whatever techniques are used, the judgment of performance assessment modelers and scientific subject experts is important to successfully completing this portion of the performance assessment (PA) process.

Event tree analyses

Event trees are one of the oldest techniques used to assess the operational safety of nuclear reactors. Probabilities can be systematically treated but the variations are mainly binary, (fault - no fault). This method describes system behavior as an event or series of events leading to system failure or loss of function. Application of the technique yields a number of combinations of basic events whose occurrence causes system failure or loss of function. These event combinations are then evaluated by various screening techniques to determine high risk scenarios. This technique is not used extensively in the context of radioactive waste disposal for several reasons including: (1) most processes are generally slow and difficult to define as abrupt events, and (2) the tree methods are not suitable to handle interaction and feedback between features, events, and processes (FEPs). In addition, the sheer number of possible combinations in an event tree can very rapidly become unmanageable.

Logic diagrams

Another technique to assist in scenario development involves the use of logic diagrams. The development of scenarios by taking combinations of the various release and transport phenomena is illustrated by the following example in Figure D-1 (NRC, 1990). Two release phenomena (R1, R2) and three transport phenomena (T1, T2, T3) create 32 possible combinations or scenarios. The use of a logic diagram, as illustrated in Figure D-1, ensures that all possible combinations of these phenomena are identified. The central scenario represents the initial conceptualization of the disposal system. All components of the engineered barrier system are assumed to perform as designed. The other scenarios are perturbations to these central conditions (e.g., assuming less than 100 percent barrier performance).

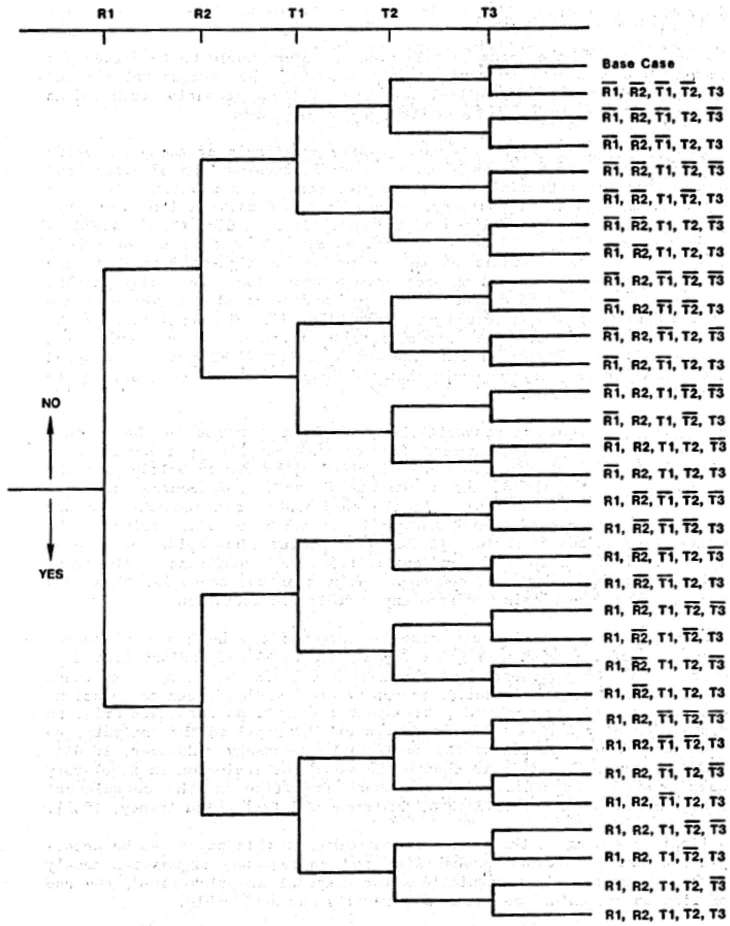

Figure D-1 Potential combinations of two release and three transport phenomena

In another example, alternative scenarios were characterized as discrete events (NRC, 2007). Climate change, floods, and introduction of irrigated agriculture are examples of discrete events affecting the hydrologic conditions at a site. These events are often not mutually exclusive (e.g., the occurrence of irrigated agriculture does not preclude the occurrence of climate change). By defining scenarios as possible combinations of alternative events, the scenarios can be made mutually exclusive. An example for three events is shown in Figure D-2. A “1” in the figure signifies the occurrence of the event in a scenario and a “0” indicates the absence of that event. Scenario 1 in Figure D-2 has none of the events occurring and might be referred to as a central scenario, perhaps characterized by the continuation of current hydrologic conditions into the future. For n events, this procedure will result in 2^n scenarios; some of these scenarios may be discarded because of an insignificant probability or because they are not of regulatory concern. Scenario development for LLW disposal is typically qualitative; exact probability values for events characterizing scenarios will usually not be available. Qualitative science-based appraisals, such as large, medium, and small, are workable substitutes. Numerical equivalents for high, medium, and low (e.g., 0.75, 0.5, and 0.25, respectively) could be used to derive estimates on the likelihood of a scenario.

Scenarios	Events Characterizing Scenarios: Climate Change (p=0.3)	Events Characterizing Scenarios: Flood (p=0.2)	Events Characterizing Scenarios: Irrigated Agriculture (p=0.6)	Scenario Probability
1	0	0	0	0.224
2	1	0	0	0.096
3	0	1	0	0.056
4	1	1	0	0.024
5	0	0	1	0.336
6	1	0	1	0.144
7	0	1	1	0.084
8	1	1	1	0.036

Figure D-2 Example formulation of mutually exclusive scenarios from three scenario-characterizing events

<u>Interaction matrices</u>

The interaction matrix methodology starts with a top-down approach to dividing the system into constituent parts. The main components are identified and listed in the leading diagonal elements of the matrix. The interactions between the leading diagonal elements are then noted in the off-diagonal elements. The convention is to allocate off-diagonal elements in the direction of contaminant migration (see Table D-1 and Figure D-3). This allows FEP interactions and pathways to be mapped, which is an important step in developing and defining a conceptual model. Moreover, the systematic process of examining how the system components relate to one another may help to identify new, previously unrecognized relevant characteristics of the system.

When using a reference list of FEPs for populating the matrix, some processes may not be allocated to any of the defined off-diagonal elements. In this case it might be necessary to subdivide some of the leading diagonal elements in particular if these processes are considered important. Introducing more divisions of the leading diagonal elements should result in a more detailed matrix and associated conceptual model (Avila, 2012). Table D-1 provides an example of a simple interaction matrix.

Table D-1 Example of a simple interaction matrix

Component A LEADING DIAGONAL ELEMENT 1,1	Influence of A on B OFF-DIAGONAL ELEMENT 1,2
Influence of B on A OFF-DIAGONAL ELEMENT 2,1	Component B LEADING DIAGONAL ELEMENT 2,2

IAEA (2004) describes this method in more detail (also see Figure D-3). The first step of the procedure of constructing an interaction matrix is to identify and define its diagonal elements. This is done by exploring how the state of the system can be described in terms of physical components and spatial and temporal extension of the system. Usually, the diagonal elements represent system state variables (such as chemical composition of water or rock stress) and the off-diagonal elements represent processes affecting the state. For example, a typical diagonal element could be "groundwater composition," which in turn can be divided into concentrations of various constituents, colloid content, and other components.

As the diagonal elements of the matrix are filled in with features or components, the interactions between them are identified and introduced into the appropriate off-diagonal elements of the matrix. All interactions should be binary (i.e. they should be direct interactions between variables in two diagonal elements and not a path via a variable in a third diagonal element). For interactions described in off-diagonal elements, the variable in the diagonal element on the row should affect the variable in the diagonal element on the column. Each off-diagonal element should be checked for interactions, and where no interaction is found marked "none."

In the process of identifying interaction, plausible interacting mechanisms are first considered without making any evaluation of the probability of occurrence or the significance of the effect. Only fully irrelevant or totally unreasonable interactions should be discarded. For each off-diagonal element the question is asked whether there are any potential events or processes that are affecting any of the variables assigned to the target diagonal element (found on the column) and at the same time are affected by any of the variables in the source diagonal element (found on the row). If the answer was yes, a short description of the interaction should be documented together with the variables in the two diagonal elements that are involved in the interaction.

In addition to the interaction matrix example, IAEA (2004) also contains Appendix B, titled "Generation of Scenarios for Near Surface Disposal Systems".

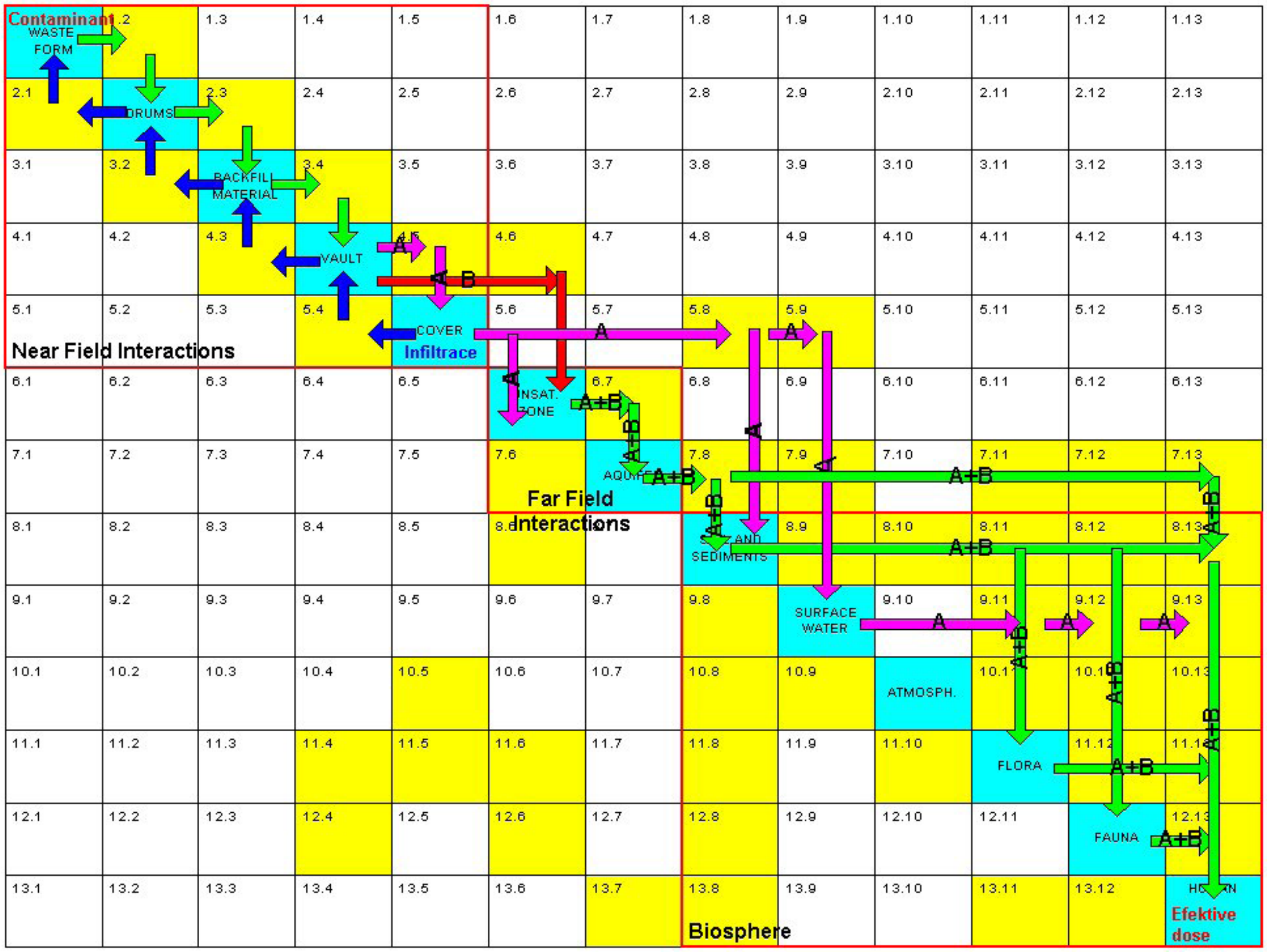

Figure D-3 Example of an interaction matrix for a central scenario including the bathtub effect (IAEA, 2004)

Influence diagrams

Influence diagrams are one of several methods to systematically evaluate and visualize FEPs that influence the disposal facility performance. The aim with these methods is to systematically identify and review all FEPs interactions and combinations that can influence the performance of the disposal system. Each process is dealt with in detail and described as an influence between features or parameters (nodes) in the system. As the number of nodes quickly rises, these influence diagrams tend to become complicated, but are usually still helpful.

In the influence diagram approach, the direction of the influence or the interactions between FEPs is shown by the use of arrows: one arrow per direct influence and one box per FEP. An example influence diagram is given by Chapman et al. (1995) for the deep repository performance assessment project in Sweden (see Figure D-4).

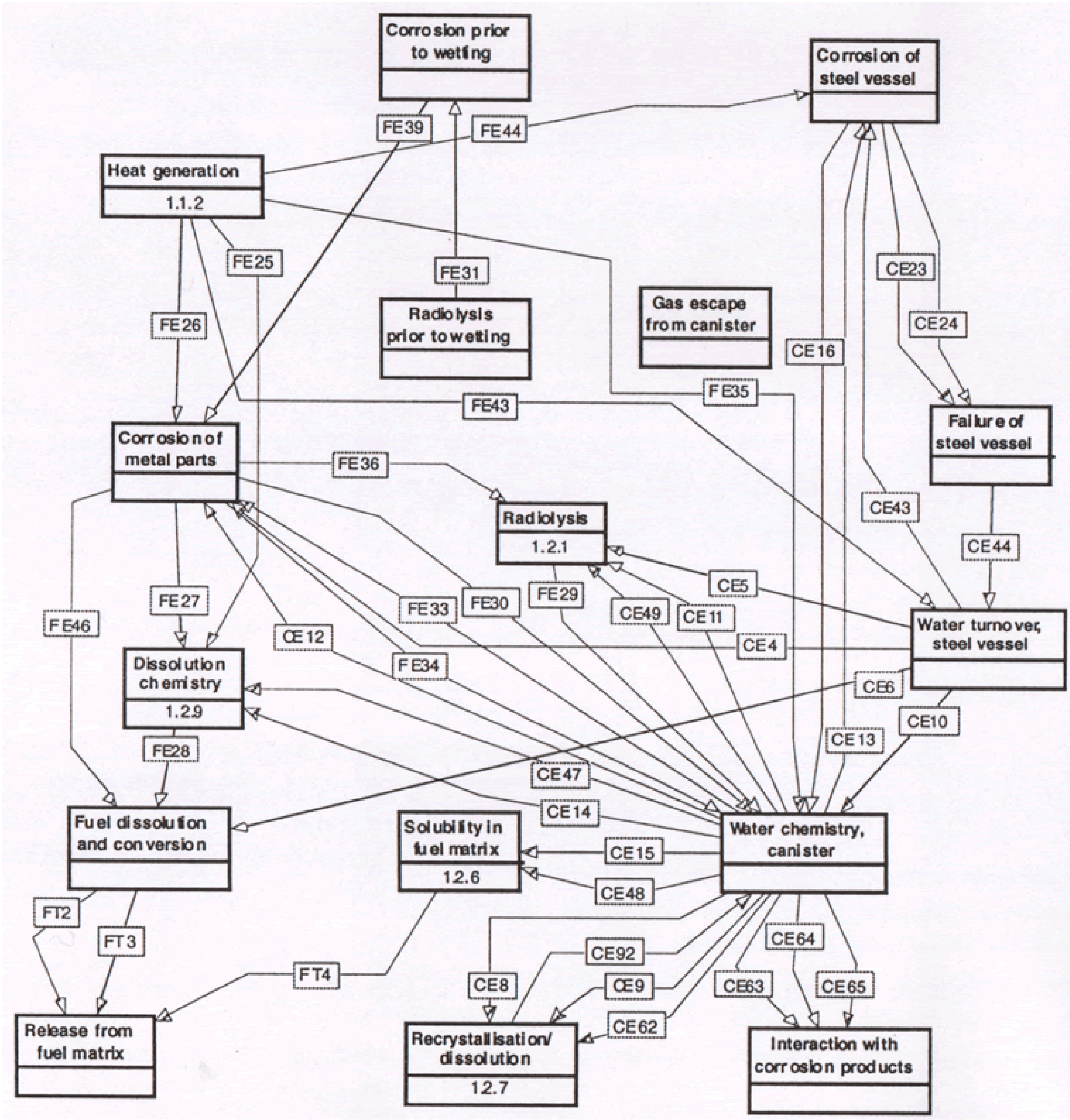

Figure D-4 Example of an influence diagram for proposed repository PA in Sweden. Many of the specific phenomena reflected in this diagram are not expected be relevant to LLW (Chapman et al., 1995)

The main steps to building the influence diagram can be summarized as follows (IAEA, 2004):

- Definition of the system barriers and selection of FEPs relevant to the defined system. The FEPs can be sorted into FEPs belonging to the system and those external scenario initiating FEPs to the system.
- Representation of the system FEPs in boxes. If a FEP is relevant for several disposal components, then it should be represented by one box for each of the disposal components.
- Identification and representation of the influences between selected FEPs. Each influence in the diagram is marked with a unique code. There are no restrictions on the number of influences between two FEPs.
- Documentation of FEPs and influences. A more comprehensive description of each FEP and influence is needed to clarify the representation.

The influence diagram should not include large disruptive events that would alter the system features since this would produce a separate, alternative scenario and would require a separate conceptual model of its own. For the influence diagram approach, process to process influences should be avoided, since it is assumed that the processes do not influence each other directly. Influences of this type should be broken in feature-process or process-feature influences. The development of influence diagrams is an iterative process. Two FEPs may be combined into one and one FEP may be split into several FEPs in order to obtain an improved representation of the system. New influences between FEPs can be identified and classified using a significance scale. This can be used to build a reduced influence diagram by removing the influences with a lower significance than a defined level. Thereafter, various influence diagrams can be developed based on the significance of the FEPs.

Judgmental approaches

Scenario formation can be made in several ways and human judgment is an important element of scenario formation. After systematic screening, the number of retained FEPs is normally too large to allow any detailed consideration of all possible combinations of them. There are, however, scenario formation procedures that allow the judgment and knowledge of qualified specialists to be integrated with quantitative considerations so that they result in a manageable number of representative scenarios.

In the judgmental method, the assessment team or invited experts select the phenomena or conditions that they believe are most important, and define possible release situations. A list of phenomena or FEPs can be used as a starting point. Documentation and transparency should not be lacking for the sake of expediency; formal and rigorous scenario development procedures are encouraged. Documents of this procedure should be sufficiently detailed to withstand detailed scrutiny by the regulatory authorities and public. Comprehensiveness and traceability in both the assessment and documentation is very important when using a judgmental approach.

REFERENCES

Avila, 2012. Avila, R., "Conceptual Model Development: Approaches, Assumptions and Level of Detail," Presentation for the "Workshop on Performance Assessments of Near-Surface Disposal Facilities: FEPs Analysis, Scenario and Conceptual Model Development, and Code Selection," U.S. Nuclear Regulatory Commission, Rockville, MD, August 29 –30, 2012.

Chapman et al., 1995. Chapman N.A, J. Andersson, P.C. Robinson, K. Skagius, C-O. Wene, M. Wiborgh and S. Wingefors, "Systems Analysis, Scenario Construction and Consequence Analysis: Definition for SITE-94," Swedish Nuclear Power Inspectorate Report No. 95:26, Stockholm, Sweden, 1995.

IAEA, 2004. International Atomic Energy Agency, "Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM), Vol. I – Review and Enhancement of Safety Assessment Approaches and Tools; Vol. II – Tests Cases," Vienna, Austria, 2004.

NEA, 1992. Nuclear Energy Agency, "Safety Assessment of Radioactive Waste Repositories: Systematic Approaches to Scenario Development." "Report of the NEA Working Group on the Identification and Selection of Scenarios for the Safety Assessment of Radioactive Waste Disposal." OECD Nuclear Energy Agency, Paris, 1992.

NRC, 1990. U.S. Nuclear Regulatory Commission, "Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure, "NUREG/CR-1667, (SAND80-1429), Washington, D.C. April 1990. https://ntrlr3.ntis.gov/view.php?pid=NTIS:NUREGCR1667

NRC, 1995. U.S. Nuclear Regulatory Commission, "Review of Scenario Selection Approaches for Performance Assessment of High-Level Waste Repositories and Related Issues," NUREG/CR-6351, (CNWRA 94-002), Washington, D.C, August 1995, ADAMS Accession No. ML040080567.

NRC, 2007. U.S. Nuclear Regulatory Commission, NUREG/CR-6940, (PNNL-16396), "Combined Estimation of Hydrogeologic Conceptual Model, Parameter, and Scenario Uncertainty with Application to Uranium Transport at the Hanford Site 300 Area," NRC: Washington, D.C. July 2007. https://ntrlr3.ntis.gov/view.php?pid=NTIS:NUREGCR6940

SKB, 2008. Svensk Kärnbränslehantering (SKB), "Project SFR 1 SAR-08: Update of priority of FEPs from Project SAFE," SKB Rapport R-08-12, ISSN 1402-3091, Stockholm, March 2008.

APPENDIX E
SITE STABILITY ASSESSMENT EXAMPLES

As discussed in Section 5.0, a licensee may use a design-based, model-based, or a combined approach to site stability assessment. The combined approach incorporates elements of both the design-based approach and the model-based approach. The licensee may use modeling to assess and improve a design. In addition, they can use a risk-based approach to the site stability assessment; if modeling demonstrates that the risks are not acceptable, the licensee can modify the disposal site design to mitigate the risk.

The NRC staff selected the West Valley Demonstration Project (WVDP) site in this appendix as an example of a model-based approach because it is presently the only example of using landform evolution modeling to evaluate site stability in an NRC-regulated or NRC-reviewed waste disposal or site decommissioning application. By use of the WVDP site example, the NRC is not approving the approach. The Department of Energy (DOE) has not yet completed its work, nor has it selected its approach to the final decommissioning of the WVDP site. However, the NRC staff believes much of the content (modeling, data collection, development of analogs) for the WVDP site is reasonably representative of what may be expected for a LLW disposal facility, and therefore, may be useful to a 10 CFR Part 61 licensee.

This appendix also provides an example of a design-based approach from the Moab, UT uranium mill tailings disposal site. A licensee of a LLW disposal facility can use the selected examples to develop an understanding of the type of information and actions involved in using the different approaches. A licensee should not use the information in these examples to justify site-specific stability assessments for LLW disposal.

Model-Based Approach: West Valley Erosion Modeling

Background

West Valley is a complex decommissioning site located in western New York State, about 50 km (30 miles) south of Buffalo (see Figure E-1). The New York State Energy Research and Development Authority (NYSERDA) holds the license and title to the 3300 acre (13.5 km^2) Western New York Nuclear Service Center (WNYNSC), originally developed as the first and only commercial spent fuel reprocessing plant to operate in the United States. The 1980 West Valley Demonstration Project (WVDP) Act gave the United States Department of Energy (DOE) exclusive possession of a 200-acre portion of the larger WNYNSC which includes the former reprocessing facility, a land disposal facility, and HLW tanks to allow DOE to carry out a number of activities, most notably, the solidification of high-level waste that had been generated as a result of spent fuel reprocessing. This 200-acre portion of the WNYNSC is referred to as the WVDP, or project premises. In conjunction with NYSERDA, DOE issued a draft environmental impact statement (DEIS) in 2008 evaluating various alternatives to decommissioning and long-term stewardship. DOE and NYSERDA selected the Phased Decision-making alternative as the preferred alternative in the final environmental impact statement (FEIS) issued in 2010 (DOE, 2010). Under the Phased Decision-making alternative, decommissioning would proceed in two phases. Phase 1 involves near-term decommissioning work (e.g., removal of the main plant process building and contaminated subsurface soils) and studies that could facilitate future decision-making for the remaining facilities and areas (see Figure E-1). A phased approach would allow additional time for technical and programmatic uncertainties to be addressed prior to making a final decision regarding decommissioning of the site. Consistent with the Phase Decision-making alternative, DOE finalized the Phase 1 Decommissioning Plan for West Valley in 2009 (DOE, 2009). NRC reviewed the plan and found it to be generally acceptable (NRC, 2010).

Decommissioning Site Characteristics

WVDP is located on the west shoulder of a steep-sided, glacially-scoured bedrock valley that is filled with a sequence of glacial sediments. These glacial deposits are comprised primarily of clays and silts separated by coarser-grained layers created during periods of glacial retreat. The site is bordered by two streams, Franks Creek to the east and Quarry Creek to the north. The WVDP is bisected by Erdmann Brook that divides the site into the North Plateau and South Plateau. Franks Creek is a tributary of Buttermilk Creek. Figure E-2 below shows major site facilities and features, as well as source areas to be addressed in Phase 1 and 2 decommissioning. Figure E-3 below shows site streams and a portion of the Buttermilk Creek watershed.

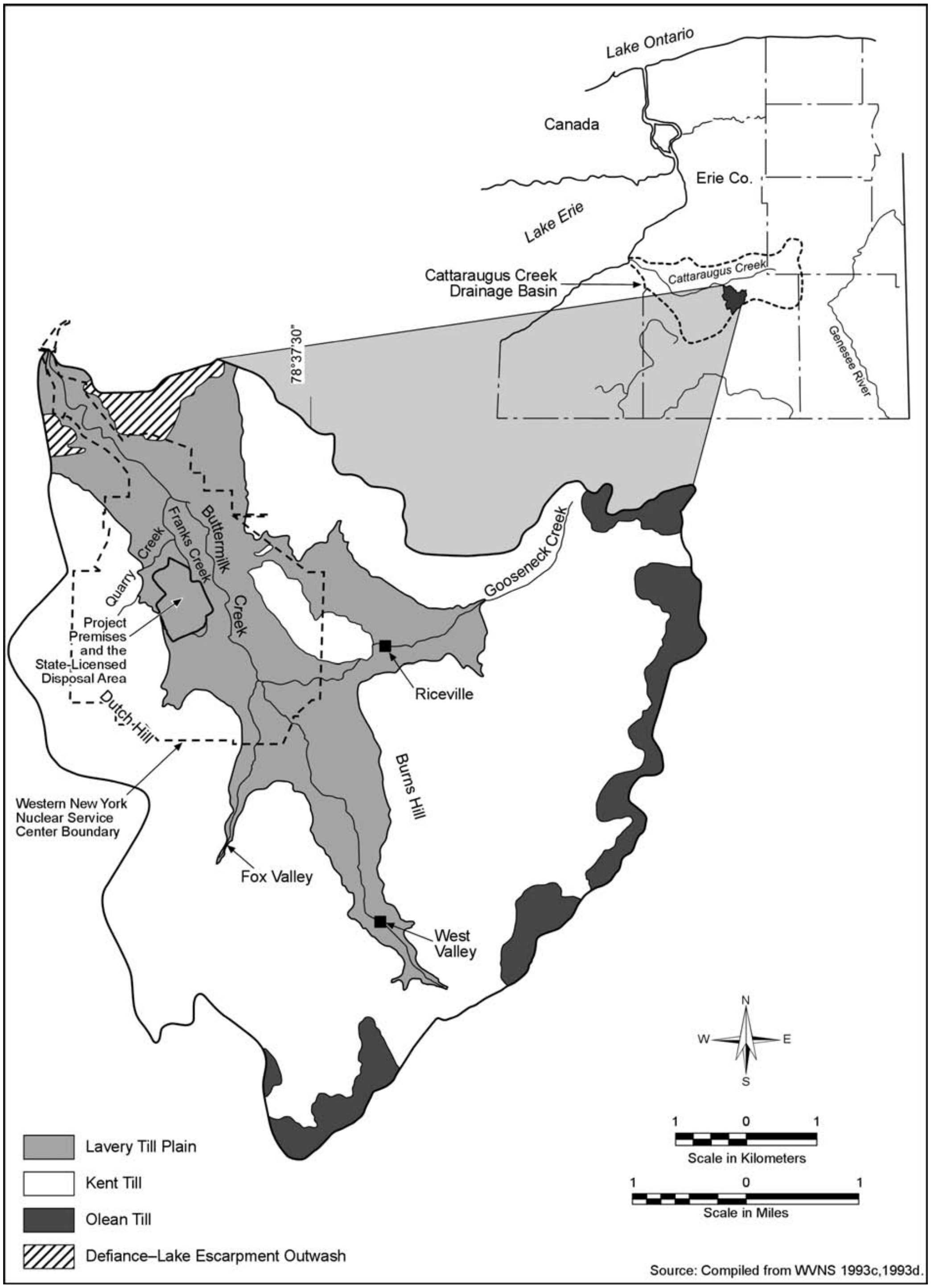

Figure E-1 Location of West Valley Site.
Image Credit: Figure F-2 (DOE, 2010)

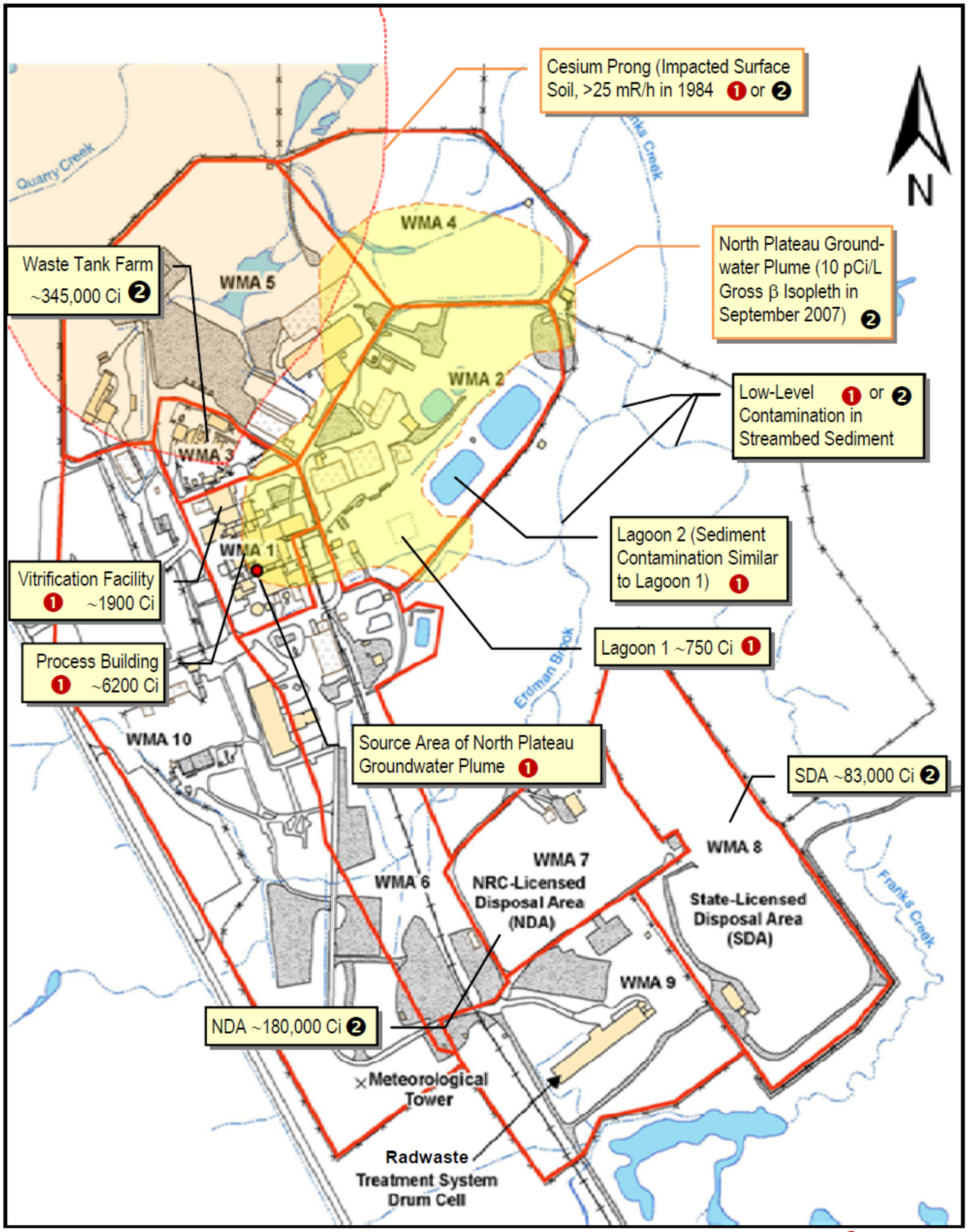

Figure E-2 Layout of West Valley Site and Source Areas to Be Addressed in Phase 1/2
Areas to be addressed in Phase 1 are marked with a ❶ symbol. Areas to be addressed in Phase 2 are marked with a ❷ symbol. Image Credit: Figure ES-5 (DOE, 2009)

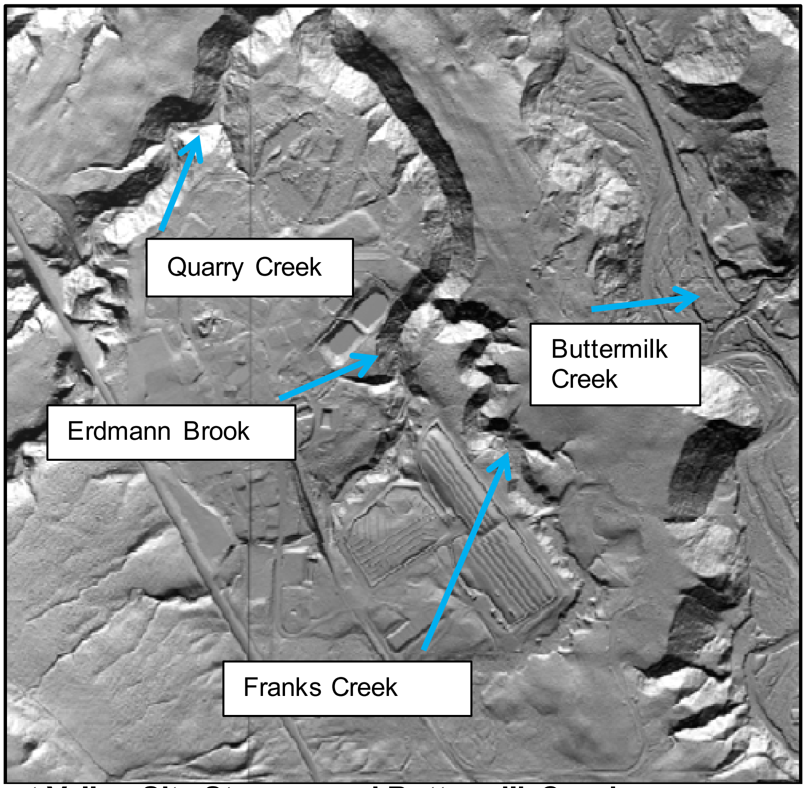

Figure E-3 West Valley Site Streams and Buttermilk Creek
Image Credit: Slide 3, Page 23, "Erosion Working Group Recommendations for Phase 1 Studies", August 22, 2012, Agenda/Presentation at http://westvalleyphaseonestudies.org/index.php/public-meeting.

As a result of site operations, WNYNSC and project premises soils, groundwater, and surface water/sediments are radiologically contaminated. Contamination includes what is referred to as the North Plateau Groundwater Plume that is characterized by high concentrations of relatively mobile and short-lived Sr-90 (see Figure E-2). The North Plateau Groundwater Plume resulted from the accidental leak of radioactive nitric acid recovered from spent fuel reprocessing operations that traveled through a floor expansion joint into soils beneath the southwest corner of the Main Plant Process Building in 1968. DOE is in the process of remediating the North Plateau Groundwater Plume including the recent installation of a permeable reactive barrier to remove Sr-90 from WVDP groundwater prior to its seepage or discharge to surface water. In Phase 2, DOE and NYSERDA must also make decisions related to closure of four tanks used to store liquid high-level waste and two radioactive waste disposal facilities, as well as final decisions regarding clean-up of radiologically contaminated areas on-site (see Figure E-2).

Decisions regarding the amount of residual radioactivity that may safely remain in contaminated surface and subsurface soils, and sediments, high-level waste tanks, treatment lagoons, and disposal areas is complicated by several technical and programmatic uncertainties that must be addressed prior to making a final decision regarding the disposition of the site. For example, one of the key technical uncertainties is the expected evolution of the landscape of the actively eroding site and the performance of engineered barriers used to minimize or mitigate the release of residual radioactivity to the environment. Phase 1 studies are proposed to address these technical uncertainties as described below.

<u>Key Site Stability Technical Issue: Erosion</u>

As stated above, erosion is a key technical issue affecting West Valley site stability. Major erosion processes affecting WNYNSC, including the WVDP, include stream channel downcutting, stream valley rim widening, gully advance, and in disturbed areas, sheet and rill erosion. Figure E-4 shows site erosion features, while Figure E-5 shows larger Buttermilk Creek watershed erosion features. Development of the current topography and stream drainage patterns began with the glaciation and retreat process that ended approximately 17,000 years ago. Erosion processes have affected site topography due to gravitational forces and water flow within the Buttermilk Creek watershed. Buttermilk Creek flows in a northwesterly direction along the central axis of the WNYNSC at an elevation of approximately 60 meters below the plateau on which the WVDP is located (see Figure E-1 and E-3). At WVDP, Franks Creek flows along the eastern boundary and drains to Buttermilk Creek. Franks Creek downcutting rates reflect base level lowering of Buttermilk Creek at the confluence of Franks Creek and Buttermilk Creek. Buttermilk Creek downcuttting rates are, in turn, affected by base level lowering of Cattaraugus Creek at the confluence of Buttermilk and Cattaraugus Creeks.

Erdmann Brook Knickpoint

Franks Creek Knickpoint

WVDP Site Gully

Figure E-4 WVDP Erosion Features

Buttermilk Creek Landslide

Figure E-5 Buttermilk Creek Watershed Erosion Features

The FEIS (DOE, 2010) includes Channel Hillslope Integrated Landscape Development (CHILD) long-term erosion modeling predictions used to evaluate the impact of erosion on site performance and the ability of various alternative end states to meet decommissioning criteria. The FEIS also provides details regarding the results of numerous other studies (e.g., erosion frame measurements, age dating of terraces to estimate stream down-cutting and stream valley rim-widening rates, aerial photography comparisons to estimate gully migration, and various short-term modeling exercises) that also help to evaluate the reasonableness of CHILD modeling predictions. However, the CHILD model was not used in earlier EIS analyses. Years of erosion work culminated in the selection of CHILD as the primary tool used by DOE in the FEIS and recommended by a DOE and NYSERDA-convened erosion working group (EWG) that made recommendations for Phase 1 studies to address the long-term effects of erosion at the site. The WVDP EWG indicated that CHILD is "the current state-of-the-art of predictive numerical landscape evolution models and embodies significant advantages and refinements compared with other generally-accepted numerical models" (2012a).

<u>West Valley CHILD Model</u>

The FEIS CHILD model domain consists of the Buttermilk Creek watershed area (see Figure E-6). Prior to predictive modeling, the CHILD model was calibrated against site data. Calibration modeling simulations begin approximately 17,000 years in the past using remnant terrace elevations and valley slope data to estimate the post-glacial (pre-incised) Buttermilk Creek watershed surface. To minimize the "butterfly effect" in which small perturbations in the initial conditions lead to notable differences in simulated drainage patterns, the existing drainage network was etched on the initial topography. Boundary conditions included the elevation history of Cattaraugus Valley at the outlet of Buttermilk Creek. As a modeling simplification, and in the absence of more detailed information about climate variation over the past 17,000 years, a constant climate was assumed. Three primary material types were selected including (i) Paleozoic bedrock, (ii) thick but unlithified glacial sediments, and (iii) shallow surface soils/sediments. Five discrete values that reflect the range of each parameter value were assigned based on site-specific measurements (e.g., water balance data), site-specific material correlations (e.g., detachment capacity related parameters), values taken from the literature for similar or analog sites (e.g., creep coefficients), or commonly accepted values (e.g., critical slope parameter). Selected calibration metrics reflect characteristics of the present-day Buttermilk Creek watershed including the (i) creek longitudinal profile, (ii) hypsometric curve (area below a certain elevation), (iii) slope-area diagram (gradient versus upstream contributing areas), (iv) width function (frequency distribution of catchment flow-path length), (v) cumulative area distribution (rate of flow aggregation), and (vi) strath terrace positions (pass/fail terrace elevation criterion considering measurement uncertainty).

Monte Carlo methods were used in the calibration process. One thousand sets of parameter values were generated by sampling the discrete parameter distributions. These 1000 sets of parameter values were run through the Buttermilk Creek watershed model described above. The results of 1000 simulations were evaluated against the calibration metrics. The scores for the first five calibration metrics were normalized to allow equal weighting of each calibration metric for subsequent averaging. Four final calibration criteria were established to select the most likely sets of parameters to be used in forward modeling projections: (i) the total average, normalized score must be greater than 0.5 (considering the first five calibration metrics listed above), (ii) the longitudinal profile score, by itself, must be greater than 0.7, (iii) the intermediate strath terrace elevation metrics should be met within a given tolerance and within a given time span, and (iv) visual agreement between the model simulation results and the current topography should be achieved. Only 5 runs passed the final four calibration criteria with the 5 sets of parameter values subsequently used in forward modeling projections to predict future erosion at WVDP.

The observed topography and “best-fit” model run topography are presented in Figure E-6. Sensitivity runs were also conducted that considered (i) wetter climates and less permeable soils, and (ii) wetter climate parameters with fast creep (for the South Plateau only). For the forward modeling projections, a digital elevation model of the current topography with a 10 m resolution was used. Additionally, a second set of model simulations were run to estimate erosion for the Sitewide-Close-In-Place alternative in which three burial mounds would remain on the North and South Plateaus. The modeling grid was refined in the area of the North Plateau and South Plateau with a grid resolution of approximately 3 m to facilitate simulation of smaller scale erosion features such as gullies. Due to the computation demands of a finer grid resolution, only one of the plateaus at the finer grid resolution could be modeled at a time, leading two separate models reflecting the mesh refinements on the North and South Plateau. With respect to boundary conditions, the final base level lowering rate from the corresponding calibration run was applied at the outlet of Buttermilk Creek. The results of the 26 modeling simulations were presented and discussed in the FEIS. The FEIS modeling results provided a reasonable approach to evaluating erosion impacts at the WVDP. However, DOE and NYSERDA acknowledged limitations of the modeling approach and recognized several areas where additional information could be collected to improve and refine erosion predictions for future Phase 2 decision-making.

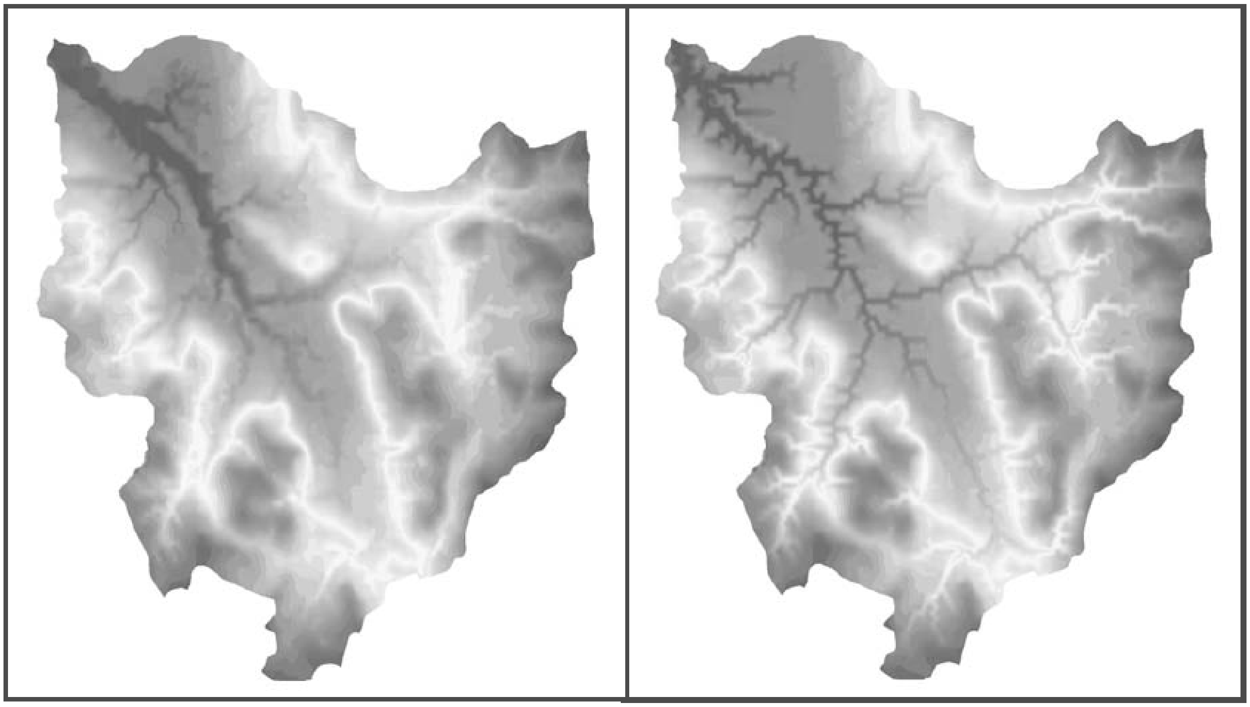

Figure E-6 Observed (left) and "Best-fit" (right) Model Run Topography
Image Credit: Figure F-8 (DOE, 2010)

Potential Additional Data Collection Efforts

DOE and NYSERDA commissioned an erosion working group to develop recommendations for studies that could be conducted during Phase 1 to further reduce uncertainty associated with the impact of erosion on site performance. The purpose of the additional studies would be to (i) fill data gaps, (ii) produce converging lines of evidence, (iii) improve scientific defensibility, and (iv) strengthen confidence in long-term erosion projections. DOE and NYSERDA are in the process of evaluating the recommendations and will determine which Phase 1 studies will be sponsored to provide additional support for erosion modeling predictions. A description of recommended studies follows.

Phase 1 studies may include the following (EWG, 2012b):

1. Terrain Analysis

The purpose of terrain analysis would be to build on previous work cited in the FEIS to better understand the post-glacial geomorphic history of the site and larger Buttermilk Creek watershed. This would provide calibration information for the numerical model and constrain important modeling parameters. For example, the geomorphic evolution of the Buttermilk Creek watershed is likely more complicated than reflected in simplified calculations of stream downcutting and valley rim widening rates based on limited age data. Stream downcutting may be slowing over time due to a slowing of glacio-isostatic rebound since recession of the Laurentide ice sheet. A better understanding of the geomorphic history of Buttermilk Creek may enable better definition of critical parameter values used for erosion modeling. The terrain analysis could include the following:

- Identification of elementary landforms or “land elements” using ArcMap (see Figure E-7a)
- Construction of geomorphic (land element) maps of WVDP, Buttermilk Creek, and potentially a companion basin site
- Performance of field reconnaissance to justify and verify potentials of mapped land elements
- Evaluation of available materials for age dating
- Development of a conceptual framework for geomorphic history of Buttermilk Creek and its base level

2. Age Dating and Paleoclimate

The purpose of age dating and paleoclimate study would be to provide additional age data to better define and constrain past rates of stream downcutting and valley rim widening for the WVDP, Buttermilk Creek watershed, and potential companion drainages; and to better understand post-glacial climate cycles and their effects on erosion processes. Data collected in this study may help constrain key modeling parameters or boundary conditions, such as the base-level history for Buttermilk Creek. The study would also provide data to improve model calibration or constrain parameter ranges. The Age Dating and Paleoclimate study could include the following:

- Excavation or examination of mapped “land elements” for age dating (Figure E-7b)
- Examination of landslide toes in channel walls or tributary gullies for buried debris to determine timing of landslide activity (landsliding mapping activities are illustrated in Figure E-7c)
- Coring of tree rings to determine times of tree deformation from landslide movements and for locate climate proxy (drought)
- Dating of post-glacial erosional and depositional features
- Evaluation of age data for possible correlation with Late Wisconsin glacial or postglacial climatic events

3. Recent Erosion and Depositional Processes

The purpose of the recent erosion and depositional process study would be to better quantify and characterize recent rates of surface and near-surface erosion and temporary sediment storage occurring on hillslopes, in regions of concentrated flow, and in stream channels at and near the facility. The scope of previous studies and measurements would be expanded to obtain more useful and complete information to inform erosion predictions at the site. This study would also collect data at a finer spatial and temporal scale than represented by the efforts in proposed studies 1 and 2. Areas of initial focus would include the two licensed disposal areas, the rim of the North Plateau, and potentially in Buttermilk Creek watershed. Key attributes of this study would include the following:

- Hillslope stability including characterization of rates and mechanisms of mass-wasting and landsliding

- Rill and gully characterization including the mapping of locations and a determination of the erodibility and erosivity of concentrated flow channels of critical concern, monitoring of flow and sediment transport (if possible)
- Stream characterization including monitoring of flow and sediment transport (if possible), assessment of knickpoint development and migration, and channel evolution (Figure E-7d)
- Surface features including identification of erosional and depositional surface forms

4. Model Refinement, Validation and Improved Erosion Predictions

The purpose of the model refinement, validation and improved erosion prediction study would be to (i) improve confidence in erosion modeling predictions through independent validation, (ii) to reduce CHILD conceptual model and parameter uncertainty, and (iii) improve CHILD model calibration. All of these activities would serve to increase confidence in the erosion modeling predictions. Study 4 activities could include the following:

- Refine CHILD model parameters, structure, and calibration using data and information collected in studies 1-3.
- Perform an independent validation test using calibrated model parameters to simulate a second (companion) drainage basin that is comparable in dimensions to similar landforms at WVDP.
- Project future erosion at the WVDP using refined and re-calibrated CHILD model; perform sensitivity and uncertainty analysis, including evaluation of the sensitivity of the results to climate.

How Does the West Valley Erosion Modeling Example Relate to 10 CFR Part 61 Guidance?

Although the West Valley erosion modeling example described above applies to a decommissioning site and has not been fully executed by DOE and NYSERDA for NRC review, the example illustrates many of the steps listed in Section 5.2.2 of this document, and reproduced below for ease of reference, that may be taken to assess performance of a 10 CFR Part 61 facility[1].

[1] Inclusion of this example does not provide any tacit or implied approval of the erosion modeling as a basis for demonstrating compliance with the radiological criteria for license termination. Such determinations will be made at the appropriate time following review of the Phase 2 decommissioning plan. The example is provided because the current approach nicely illustrates the components of a model-based stability assessment.

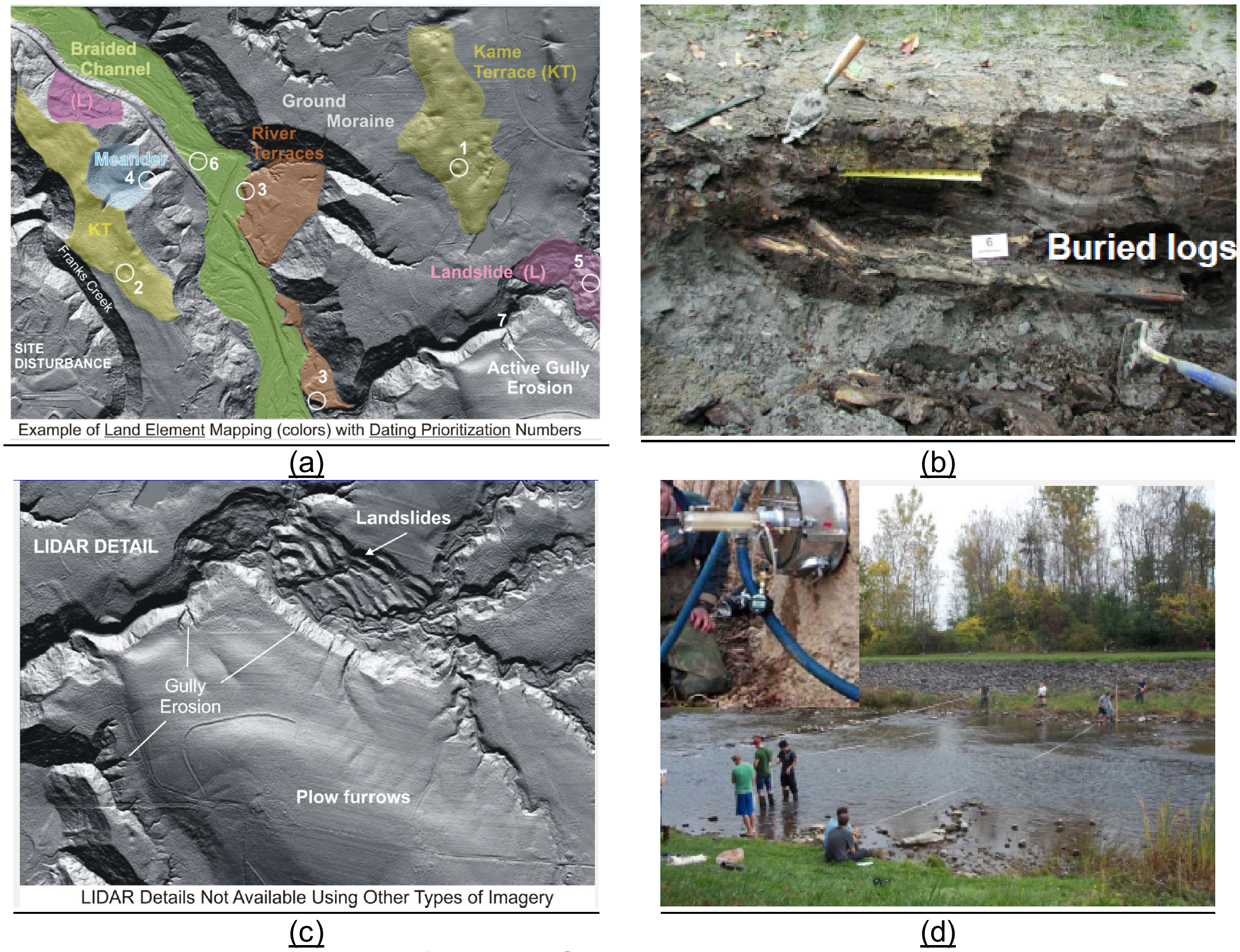

Figure E-7 Potential Phase 1 Erosion Studies
Image Credit: "Erosion Working Group Recommendations for Phase 1 Studies", August 22, 2012, Agenda/Presentation at http://westvalleyphaseonestudies.org/index.php/public-meeting.

These steps include the following:

- Define model objectives
- Develop or select the model
- Document and provide the basis for assumptions
- Parameterize the model
- Calibrate the model
- Verify the model
- Characterize uncertainty
- Provide model support
- Iterate, if necessary

Data collection and modeling of WVDP erosion has proceeded in an iterative fashion with erosion analyses building on previous work and erosion modeling continuing to improve over time as additional information is obtained. The code selection process began with the initial evaluation of various shorter-term, smaller scale models that evaluated one or two key erosion processes operable at the WNYNSC and WVDP but that were limited in their ability to simulate multiple, coupled erosion processes over larger time and spatial scales. DOE also attempted more sophisticated landscape evolution modeling using codes such as SIBERIA in earlier EIS analyses. All of these modeling exercises led to the ultimate selection of the CHILD model that is considered the state-of-the-art in landscape evolution modeling. Due to the complexity of the site, landscape evolution modeling was considered necessary to provide technically defensible erosion modeling predictions to facilitate consensus decision-making.

DOE used site-specific data or measurements, literature information from analog sites and finally generic information sources, if more relevant data were not available to assign CHILD modeling parameters. DOE used a calibration process to identify the most likely set of parameter values to predict future erosion at the site. DOE also used site data and other shorter-term modeling results to evaluate the reasonableness of CHILD modeling results. DOE performed Monte Carlo analysis to evaluate the impact of parameter uncertainty on the results of the analysis. DOE attempted to reduce uncertainty in the erosion predictions through selection of “best-fit” parameter values in the calibration process that were able to produce current day topography. DOE performed sensitivity analysis to evaluate “what-if” scenarios such as a wetter climate or faster creep coefficients. DOE documented the results of its erosion analyses in the FEIS including a discussion regarding potential model limitations. DOE provided information on areas for potential improvement, including the collection and use of additional data or additional analyses that might be conducted as code capabilities matured. Phase 1 studies have been recommended by the WVDP erosion working group and will be considered by DOE and NYSEDA to further reduce uncertainty and provide additional support for erosion modeling predictions.

As indicated in Section 5.2.2.2, a model-based approach, similar to what was performed for WVDP erosion modeling analyses, is typically used for longer-term analyses. A design-based approach may also be justified for relatively shorter time periods. An example of a design-based approach is provided in the next section. A hybrid approach may also be used for assessments of site stability and could help provide multiple lines of evidence that the performance objectives in 10 CFR Part 61, Subpart C will be met. For example, support may be provided for the performance of a particular design for some period of time that mitigates the risk of relatively short-lived waste. Over longer time periods, the performance of the design may be less certain. Sensitivity analyses could be performed to evaluate the impact of various levels of underperformance of the design over time to evaluate the acceptability of the design and the ability of the site to meet performance objectives, lending confidence to the compliance and performance period analyses. As illustrated in the next example, the model- and design-based approaches share many common features (NRC, 2008).

Design-Based Approach: Moab UT Example:

FINAL

TECHNICAL EVALUATION REPORT

for the

PROPOSED REMEDIAL ACTION

of the

MOAB, UTAH

URANIUM MILL TAILINGS SITE

July 2008

Division of Waste Management
and Environmental Protection
Office of Federal and State Materials
and Environmental Management Programs
U.S. Nuclear Regulatory Commission

4.0 SURFACE WATER HYDROLOGY AND EROSION PROTECTION

4.1 Introduction

This section of the TER describes the staff's review of surface water hydrology and erosion protection issues related to long-term stability. In this section, the staff provides the technical bases for the acceptability of the licensee's erosion protection design. The RAP was reviewed against the EPA requirements presented in 40 CFR Part 192, Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings using Section 3.0 of the Final Standard Review Plan for the Review and Remedial Action of Inactive Mill Tailings Sites Under Title I of the Uranium Mill Tailings Radiation Control Act (NRC, 1993). Review areas that are covered include: estimates of flood magnitudes; water surface elevations and velocities; sizing of riprap to be used for erosion protection; long-term durability of the erosion protection; and testing and inspection procedures to be implemented during construction.

4.2 Hydrologic Description and Site Conceptual Design

To comply with 40 CFR 192, which requires stability of the tailings for 1000 years to the extent reasonably achievable and in any case for 200 years, DOE proposes to construct a disposal cell to protect the contaminated material from flooding and erosion. The design basis events for design of erosion protection include the Probable Maximum Precipitation (PMP) and the Probable Maximum Flood (PMF) events, both of which are considered to have very low probabilities of occurring during the 1000-year stabilization period.

As shown in Figure 6-3 of the Remedial Action Selection Report (RAS), the top surface of the cell will be configured to drain in various directions at a slope of about two percent, and the embankment side slopes will be constructed on a 1 vertical (V) on 5 horizontal (H) slope. To protect against erosion, the top and side slopes will be covered with layers of rock riprap. At the toes of the side slopes, rock riprap aprons will be constructed to provide protection against the potential migration of gullies toward the disposal cell. Several drainage channels will be constructed to convey flood flows off the disposal cell and away from the disposal area.

4.3 Flooding Determinations

The computation of peak flood discharges for various site design features was performed by DOE in several steps. These steps included: (1) selection of a design rainfall event;
(2) determination of infiltration losses; (3) determination of times of concentration;
(4) determination of appropriate rainfall distributions and intensities, corresponding to the computed times of concentration; and (5) calculation of flood discharge. Input parameters were derived from each of these steps and were then used to calculate the peak flood discharges to be used in the final determination of rock sizes for erosion protection.

4.3.1 Selection of Design Rainfall Event

One of the phenomena most likely to affect long-term stability is surface water erosion. To mitigate the potential effects of surface water erosion, the staff considers that it is very important to select an appropriately conservative rainfall event on which to base the flood protection designs. Further, the staff considers that the selection of a design flood event should not be based on the extrapolation of limited historical flood data, due to the unknown level of accuracy associated with such an extrapolation. DOE utilized a PMP computed by deterministic methods (rather than statistical methods) and based on site-specific hydrometeorological characteristics. The PMP has been defined as the most severe reasonably possible rainfall event that could occur as a result of a combination of the most severe meteorological conditions occurring over a watershed. No recurrence interval is normally assigned to the PMP; however, the staff has concluded that the probability of such an event being equaled or exceeded during the 1000-year stability period is very low. Accordingly, the PMP is considered by the NRC staff to provide an acceptable design basis.

Prior to determining the runoff from the drainage basin, the flooding analysis requires the determination of PMP amounts for the specific site location. Techniques for determining the PMP have been developed for the United States by Federal agencies in the form of hydrometeorological reports for specific regions. These techniques are widely used and provide straightforward procedures with minimal variability. The staff, therefore, concludes that use of these reports to derive PMP estimates is acceptable.

PMP values were estimated by DOE using Hydrometeorological Report No. 49 (HMR-49). A 1-hour PMP of 8.2 inches was used by DOE as a basis for estimating PMFs for the small areas at the site such as the top and side slopes. These procedures for estimating PMP values were reviewed, and it was concluded that the PMP amounts are acceptable for the small drainage areas at the site.

4.3.2 Infiltration Losses

The determination of the peak runoff rate is also dependent on the amount of precipitation that infiltrates into the ground during its occurrence. If the ground is saturated from previous rains, very little of the rainfall will infiltrate and most of it will become surface runoff. The loss rate is highly variable, depending on the vegetation and soil characteristics of the watershed. Typically, all runoff models incorporate a variable runoff coefficient or variable runoff rates. Commonly-used models such as the U.S. Bureau of Reclamation (USBR) Rational Formula (USBR, 1977) incorporate a runoff coefficient (C); a C value of 1 represents 100% runoff and no infiltration. Other models such as the U.S. Army Corps of Engineers Flood Hydrograph Package HEC-1 (COE, 1988) separately compute infiltration losses within a certain period of time to arrive at a runoff amount during that time period.

In computing the peak flow rate for the small drainage areas at the site, DOE used the Rational Formula (USBR, 1977). In this formula, the runoff coefficient was assumed to be 1.0; that is, DOE assumed that no infiltration would occur. Based on its conservatism, the staff concludes that this is an acceptable assumption.

4.3.3 Times of Concentration

The time of concentration (t_c) is the amount of time required for runoff to reach the outlet of a drainage basin from the most remote point in that basin. The peak runoff for a given drainage basin is inversely proportional to the time of concentration. If the time of concentration is assumed to be smaller, the peak discharge will be larger. Times of concentration and/or lag times are typically computed using empirical relationships such as those developed by Federal agencies. Velocity-based approaches are also used when accurate estimates are needed.

Such approaches rely on estimates of actual flow velocities to determine the time of concentration of a drainage basin.

Times of concentration for the riprap design were estimated by DOE using an average of several methods, including the Kirpich Method (USBR, 1977). These methods are generally accepted in engineering practice and are considered by the staff to be appropriate for estimating times of concentration at this site. Based on a review of the calculations provided, the staff concludes that the t_c values used by DOE were acceptably derived.

4.3.4 Rainfall Distributions and Intensities

After the PMP is determined, it is necessary to determine the rainfall intensities corresponding to shorter rainfall durations and times of concentration. A typical PMP value is derived for periods of about one hour. If the time of concentration is less than one hour, it is necessary to extrapolate the data presented in the various hydrometeorological reports to shorter time periods.

To determine peak flood flows for the cell, DOE developed a rainfall depth-duration curve using guidelines in NUREG-1623 and calculated the rainfall intensities for the small drainage areas at the site to be about 28-54 inches per hour. Based on a review of this aspect of the flooding determination, the staff concludes that the computed peak rainfall intensities are acceptable.

4.3.5 Computation of PMF Discharges

To estimate PMF peak discharges for the top and side slopes, DOE used the Rational Method (Chow, 1959). This method is a simple procedure for estimating flood discharges that is recommended in NUREG-1623 (Johnson, 2002). In using the Rational Method, DOE assumed a runoff coefficient equal to 1.0 and a flow concentration factor of 3. For a maximum top slope length of about 1300 feet (with a slope of 0.02) and a side slope length of about 180 feet (with a slope of 0.2), DOE estimated the peak flow rates to be about 1.28 cubic feet per second per foot of width (cfs/ft) for the top slope and 1.33 cfs/ft for the side slope. PMF flow rates for the downstream aprons were estimated by DOE and are similar to the flow rates for the side slopes.

PMF flow rates for the channels were calculated by DOE and represent an accumulation of flows down the side slopes and offsite runoff. For the various channels and drainage structures, DOE used the SCS unit hydrograph method (USBR, 1987) to calculate peak PMF flows. Based on a review of the calculations, including the time of concentration, rainfall intensity, and runoff, the staff concludes that DOE's estimated flow rates are acceptable.

4.4 Erosion Protection

The ability of a riprap layer to resist the velocities and shear forces associated with surface flows over the layer is related to the size and weight of the stones which make up the layer. Typically, riprap layers consist of a mass of well-graded rocks which vary in size. Because of the variation in rock sizes, design criteria are generally expressed in terms of the median stone size, D_{50}, where the numerical subscript denotes the percentage of the graded material that contains stones of less weight. For example, a rock layer with a minimum D_{50} of 4 inches could contain rocks ranging in size from 0.75 inches to 6 inches; however, at least 50% of the weight of the layer will be provided by rocks that are 4 inches or larger. Depending on the rock source, variations occur in the sizes of rock available for production and placement, and it is therefore necessary to ensure that these variations in rock sizes are not extreme. Design criteria for developing acceptable gradations are provided by various sources (e.g., Simons and Li, 1982), and examples of acceptable gradations may also be found in NUREG-1623.

4.4.1 Sizing of Erosion Protection

Riprap layers of various sizes and thicknesses are proposed for use at this site, and the design of each layer is dependent on its location and purpose. To reduce the number of gradations that need to be produced, DOE will place larger rock in some areas than is required. For ease of construction and to minimize the number of gradations, DOE has purposely over-designed several areas by providing larger rock than needed in many areas of the slopes and channels.

4.4.1.1 Top Slopes, Side Slopes, and Aprons

The portion of the top slope that drains to the south will be protected by a 6-inch thick layer of rock with a minimum D_{50} of about 1.8 inches. The area of the top slope draining to the north will be protected by a 6-inch layer of rock with a minimum D_{50} of 1.2 inches. Based on a review of the proposed gradation specifications, the minimum D_{50} that will be provided is about 2 inches, which is conservative.

For the north side slope of the cell, DOE proposes to use an 8-inch layer of rock with a minimum D_{50} of about 4 inches. The south side slope will be covered with a 12-inch layer of rock with a D_{50} of about 6 inches. The east and west side slopes will be protected by 6-inch layers of rock with a minimum D_{50} of 2 inches. Methods suggested in NUREG-1623 were used to determine the required rock sizes.

To protect the toe of the disposal cell and to dissipate the energy as the side slopes transition to natural ground, DOE will construct aprons along the toe of the side slopes. The area along the base of the south side slope will be protected by a rock toe/apron with a minimum D_{50} of 12 inches, while the toe of the north side slope will be protected by rock with a minimum D_{50} of 8 inches. The volume of rock was computed using a minimum depth of 3 times the D_{50} size and an apron width of 15 times the D_{50} size, or 10 feet, whichever is greater. The design criteria suggested in NUREG-1623 were used to determine rock sizes and rock volumes for the toe aprons.

Based on staff review of DOE's analyses and the acceptability of using design methods recommended by the NRC staff, the staff concludes that the proposed rock sizes for the top slopes, side slopes, and aprons are adequate.

4.4.1.2 Diversion Channels

DOE proposes to construct diversion channels at various locations in the area of the disposal cell. DOE developed peak PMF flows, rock sizes, and scour depths in accordance with methods recommended in NUREG-1623. Based on a check of the computations, the staff concludes that the peak flows, rock sizes, and scour depths are acceptable.

4.4.1.3 Channel Outlets

The diversion channels will extend several hundred feet past the edge of the disposal cell to prevent flows from directly impacting the cell side slopes. The channels will convey flows to the east and west sides of the cell and then will turn southward. At the end of the channels, the channels will be widened (termed flow "spreaders" by DOE). At the downstream end of the flow spreaders, additional rock will be provided to prevent gully headcutting into the spreaders. To reduce rock sizes to manageable levels, DOE intends to construct a pre-formed slope of 1V on 10H, and this slope will be extended to the expected scour depth. Staff review of the design of the riprap for the channel outlets indicates that the rock is large enough and extends to a sufficient depth to resist gully intrusion.

4.4.1.4 Sediment Considerations

The north side of the disposal cell would normally receive runoff directly from the area between Book Cliffs and the cell. This area will be protected by constructing a barrier using a very large quantity of excess excavated material (the "wedge"), which will act as a diversion berm to re-direct runoff away from the disposal cell. An access road between the cell and the wedge will be left in place. Runoff from the south side of the wedge will flow to the east and west in a ditch along the north side of the road, and runoff from the disposal cell will flow east and west along the south side of the road. See Figure 6-7 of the RAS.

The wedge will provide protection for the disposal cell by reducing the amount of runoff that is carried in the diversion channels to the north of the cell. Also, the wedge will reduce the amount of sediment entering the diversion channels. DOE performed sediment analyses to show that the wedge will accumulate sediment on its north side, but will be capable of re-directing flows away from the disposal cell.

DOE's analyses indicate that sediment will be produced on the south slope of the wedge and that sediment from the wedge will fill and overtop the unlined channel north of the access road. This excess sediment will be deposited in the rock-lined channel south of the road. DOE provided analyses to show that the riprap sizes are large enough to resist the increased velocities associated with a reduction in channel capacity and an increase in discharges associated with overtopping of the unlined channel.

4.4.2 Riprap Gradations

Riprap gradations for each of the different rock sizes and layers were selected by DOE using basic gradation criteria Based on review of the gradations provided, each layer thickness, gradation, and minimum rock size is acceptable.

4.4.3 Rock Durability

The previous sections of this TER examined the ability of the proposed erosion protection design to withstand flooding events reasonably expected to occur in a 1000- year period. In this section, rock durability is evaluated to determine if there is reasonable assurance that the rock itself is durable and will survive and remain effective for 1000 years. Rock durability is defined as the ability of the rock to withstand the forces of weathering. Therefore, rock durability is a key factor in evaluating the long-term stability of the rock cover. For rock to remain effective to control erosion, the rock size selected should not be reduced by weathering processes. Therefore, if the rock size used for the cover does not diminish over the 1000-year compliance period, its ability to control future erosion will be sustained. However, uncertainties exist with estimating future rock durability for 1000 years. As a result, NRC guidance identifies three evaluations of rock durability to provide multiple and complimentary lines of evidence and greater confidence in the sustained durability of the rock source selected. These evaluations are: 1) rock durability testing and scoring; 2) absence of adverse minerals and heterogeneities; and 3) evidence of resistance to weathering. Information for each of these evaluations was provided by DOE and the staff's review is described below.

4.4.3.1 Selection and Description of Rock Type and Source

Description of the rock types and deposit that is proposed for the rock source is important to understanding the variability of the deposit or formation containing the proposed rock source (e.g. percentage of each rock type), and the variability within the proposed rock source (e.g. different fabrics that could affect rock durability and resistance to weathering). Understanding the variability of the deposit/formation and each rock type are important to obtaining representative samples for durability tests and developing rock production procedures that may be needed to mitigate adverse rock types in the deposit/formation.

DOE has selected a basalt as a rock source from a site approximately four miles east of Fremont Junction, Utah, which is approximately 95 miles west of the Crescent Junction site. NRC approved DOE's use of this rock source in 1988 for its use in the erosion cover for the Green River UMTRA disposal cell in Green River, Utah. The Fremont Junction site consists of 400 acres of property owned by the State of Utah School of Institutional Trust Lands Administration that has been permitted for the purpose of mining ordinary sand and gravel. The basalt-bearing deposit at the Fremont Junction site is a Quaternary pediment-mantling alluvial deposit of Quaternary age.

DOE's selection of the Fremont Junction basalt is based on the combined results of the 1988 evaluations of the basalt for the Green River disposal cell and the recent studies in 2007 and 2008 for the Crescent Junction site. The 1988 evaluations consisted of field observations at two test pits, durability tests, petrographic analyses, and x-ray diffraction analyses. The 2007 and 2008 evaluations include field observations at eight test pits, durability tests, observations of the basalt on the Green River disposal cell, and natural analogue studies that provide evidence of long-term resistance to weathering. The basalt used at Green River was excavated from the same alluvial deposit about one mile northeast of the areas that would be excavated for the Crescent Junction site. Therefore, the 1988 petrographic analyses and x-ray diffraction analyses were used and not repeated in 2008.

The Fremont Junction deposit includes an overburden layer at the surface that is approximately eight feet thick that consists of clayey sand and clayey silt with a small percent of basalt clasts with caliche crusts, a reddish relic soil layer, and in places a white calcified zone. Beneath the overburden layer is the alluvial deposit that is at least 20 feet thick and consists of 15-45 % subrounded cobbles and boulders of basalt and other rock types such as tan sandstone, limestone, chert, and quartzite. Matrix material supports the cobbles and boulders and consists of sand and gravel up to three inches. DOE's rock production procedures discussed in Section 4.4.4, include screening to separate the matrix material from the cobbles and boulders of basalt and non-basalt that would then be crushed to the sizes specified for use as cover material.

Based on the estimates of rock types and alluvial deposit thickness, DOE estimates that the volume of useable rock should be at least twice the volume required by the design of the erosion cover.

DOE estimates that the cobble and boulder portion of the alluvial deposit includes about 95% dark gray basalt and 2-3% red basalt. These two types of basalt were likely derived from two different sources that are 15 to 20 miles southwest and south-southwest of the site. The remaining non-basalt lithologies in the alluvial deposit make up about 2-3%. The tan sandstone and limestone cobbles and boulders are soft and nondurable, whereas the chert and quartzite cobbles appeared to be at least as hard and durable as the basalt. The estimates of the non-basalt lithologies and their respective rock durability scores are important to conclusions about how much of this material is acceptable and unacceptable for use. The rock production procedures in Section 4.4.4 discuss how the unacceptable material, such as the tan sandstone, would be removed from the deposit either by crushing, which would reduce its percentage further, or removal of the boulders before crushing.

4.4.3.2 Rock Durability Testing and Scoring

Rock durability testing and scoring following the procedures in NRC's guidance in NUREG-1623 is one of the evaluations DOE used for determining the acceptability of the Fremont Junction rock source for its Crescent Junction erosion protection cover. This evaluation procedure provides a consistent and quantitative way to evaluate rock sources at NRC regulated sites using ASTM tests for parameters that are good indicators of rock durability (i.e., specific gravity, absorption, sodium sulfate soundness, and L/A abrasion).

DOE provided durability test data of samples from the Fremont Junction area collected in 1988 and 1989 for the Green River disposal cell and in 2007 and 2008 for the Crescent Junction site. Tests were conducted on samples from the gray and red basalts. Results from specific gravity, absorption, sodium sulfate soundness, and L/A abrasion tests were provided and then used to develop rock scores following NRC's guidance in NUREG-1623.

The scores of the 1988 samples for the Green River disposal cell ranged from 66.7% to 79.4%. The sample that scored 66.7% was described in the 1988 report as severely weathered. However, DOE's 2008 evaluation concludes that these samples were likely the vesicular red basalt. DOE's 1988-1989 quality control testing and scoring of four samples collected during the placement of the basalt cover at the Green River disposal cell resulted in additional and higher scores for the Fremont Junction basalt. Scores for the Type A rip rap ranged from 78 to 90% with an average of 85%. Scores for the Type B rip rap ranges from 80 to 90 % with an average of 83%.

DOE's scores from the 2007 and 2008 samples provided additional results. The gray basalt, which makes up approximately 95% of the alluvial deposit, had scores of 82.9 and 83.3. These scores exceed the 80% score that indicates a high quality rock that can be used for most applications according to NRC's guidance. The red basalt that makes up approximately 2-3% of the basalt had a score of 63.7 which is similar to the 1988 initial score. Although the 63.7% score is lower than the gray basalt, it is in the range for rock that would be acceptable for use in non critical areas. DOE noted that the sample of the red basalt was softer than the gray basalt; possibly because it was vesicular. During the June 25, 2008 site visit, field observations of cobbles and boulders of dense non-vesicular red basalt appeared to both DOE and NRC staff to be more competent than the vesicular red basalt that had a low score.

4.4.3.3 Absence of Adverse Minerals and Heterogeneities

DOE used information from field observations and the 1988 petrographic and x-ray diffraction analyses to identify if adverse heterogeneities or adverse minerals were present that could be vulnerable to weathering. Field observations were used to identify large scale adverse heterogeneities such as the undesirable overburden layer and fine grained matrix sediments supporting the cobbles and boulders in the overall deposit. As discussed in Section 4.4.1, DOE proposes to remove the overburden layer before excavation of the basalt alluvial deposit. DOE also proposes to screen out the finer matrix material from the basalt cobbles and bounders.

The petrographic and x-ray diffraction analyses were used to identify if adverse minerals that could be susceptible to weathering, such as olivine and clay, are present and if so in what amounts. DOE's 1988 petrographic analyses concluded that the samples lacked significant amounts of adverse minerals such as calcite, clays, olivine, and feldsphathoids. X-ray diffraction analyses determined that the basalt samples contained only 1% olivine.

The field observations and petrographic analyses also identified the non-basalt lithologies in the deposit and those lithologies that might be unacceptable and excluded by rock processing procedures. The non-basalt lithologies making up about 2-3% of the cobbles and boulders, consist of tan sandstone, limestone, chert, and quartzite. The sandstone appeared to be friable in field observations. The petrographic analysis of the sandstone indicated surface weathering is moderate and consists of pitting due to leaching of carbonate grains that penetrated one quarter of an inch. The 6% calcite occurred as recrystalized limestone grains and the 5% clay occurred as rock fragments. Although this undesirable sandstone makes up a very small part of the cobbles and boulders, as discussed in Section 4.4.1, DOE proposes to minimize this lithology by crushing and screening as well as removal of large boulders, if necessary.

4.4.3.4 Evidence of Resistance to Weathering

Evidence of resistance to weathering can be both direct and indirect. DOE's 2007 and 2008 field observations of the eight test pits did not show evidence of significant weathering of the basalt such as weathering rinds. To confirm these observations and to resolve the 1988 report of an upper weathered zone and weathering rinds on the red basalt, DOE also observed the crushed basalt used on the cover of the Green River disposal cell and the subrounded basalt boulders in the Green River channel. This basalt from the same deposit at Fremont Junction provided a large "exposure" of the basalt that was clean and free of the fine material and dust that limited observations in the test pits at Freemont Junction. DOE did not observe any weathering rinds on either the dark gray or red basalt. DOE concluded that the descriptions of weathering rinds from the 1988 investigation possibly were interpreted to be the thick caliche crusts on some basalt clasts. Thus, more recent DOE investigations, as well as NRC observations during a site visit, confirm the absence of weathering zones or weathering rinds on the Fremont Junction basalt.

The only evidence of basalt weathering was the leaching of olivine crystals by chemical weathering on the surface of a sample observed in the 1988 petrographic analyses. This analysis also noted that the olivine crystals observed in the interior of the sample had not been weathered. As mention above, the x-ray diffraction analysis indicated that olivine only made up 1% of the sample analyzed.

Because of the absence of quantitative weathering rate studies for basalt as well as other rock types, NRC's guidance in NUREG-1757 notes that indirect evidence of resistance to weathering can add confidence in the durability and slow weathering of rock types selected for long-term erosion protection. DOE identified the following geologic analogues to show that the Fremont Junction basalt has remained resistant to weathering for thousands of years and well beyond the 1000-year regulatory period required.

- Basalt boulders may have resisted weathering for 500,000 years based on the estimated age of the alluvial deposit, using a published steam downcutting rate for this part of the Colorado Plateau.
- Basalt boulders have resisted weathering for possibly 8,000 to 10,000 years based on the estimated age of wind-fluted surfaces on exposed basalt boulders caused by wind driven sand.
- Rock varnish on exposed basalt boulders may have been formed several thousand years ago.
- Lichen cover on exposed basalt boulders may have been in place for hundreds of years.
- Basalt boulders buried at depths of three to six feet in the overburden commonly have white calcium carbonate crusts, which can take tens of thousands of years to form, indicating these boulders have been in place for many thousands of years without noticeable weathering effects.

4.4.3.5 Conclusions

Based on the review of DOE's evaluations, the staff concludes that: 1) durability test results and scores demonstrate acceptable physical properties of the Fremont Junction basalt; 2) adverse minerals such as olivine and clay are present in very small amounts (1%) and adverse heterogeneities, such as friable sandstone and matrix sand and gravel, can be identified and avoided when rock is excavated or screened and crushed in processing: 3) there is direct evidence from the Fremont Junction deposit and Green River disposal cell cover of the absence of weathering such as weathering rinds; and 4) indirect evidence from natural basalt analogues add confidence that basalt weathering rates are slow and the basalt has resisted weathering for thousands of years at the Fremont Junction area. Based on these evaluations, the staff concludes that the Fremont Junction basalt is durable and should resist weathering and associated size reduction for at least the 1000 year compliance period. Therefore, the staff considers that the Fremont Junction basalt is acceptable for use in the erosion controls at the Crescent Junction site. This conclusion is consistent with NRC's previous approval of the basalt for use at the Green River disposal cell.

4.4.4 Testing and Inspection of Erosion Protection

DOE provided information regarding testing, inspection, and quality control procedures to be used for the erosion protection materials.

4.4.4.1 Rock Selection During Production

As discussed above, DOE has selected the Fremont Junction basalt as it rock source. Based on information provided by DOE in Sections 6.6 and 6.7 of the RAP and as discussed above in Section 4.4.3.1, it appears that the rock in the proposed quarry could be somewhat variable, depending on the location where rock will be produced within the quarry. DOE provided information to document the quality assurance and quality control (QA/QC) procedures that will be implemented during rock production to address this variability and to assure that rock of acceptable quality will consistently be produced.

The overall goal of the rock selection procedure is to minimize the potential that unsuitable rock is produced. To accomplish this, DOE intends to strip overburden from the alluvial deposits and to stockpile this material in a manner where it is separated from the basalt cobbles and boulders. Rock materials will be excavated, crushed, and screened into stockpiles of various sizes. The rock will then be crushed and further screened, as necessary, to produce the required rock sizes. These primary and secondary sorting processes should assure that rock will be relatively homogeneous and that visible portions of the stockpiles will be representative of the entire stockpile. Crushing and screening will also remove significant amounts of weak, friable materials (i.e., tan sandstone and limestone), resulting in a product that contains only limited amounts of poor-quality materials. In the unlikely event that a stockpile contains significant unacceptable rock, the lower quality material (i.e., tan friable sandstone and limestone) would be extracted to assure that no more than 10% by volume is present in the final product.

On June 26, 2008, the staff directly observed the Fremont Junction site. Based on observations during that site visit and information provided by DOE in Sections 6.6 and 6.7 of the RAP, the staff concludes that the proposed program for rock production is acceptable.

4.4.4.2 Durability Testing

DOE proposes that rock durability testing will be performed a minimum of four times and/or at a frequency of one test for every 10,000 cubic yards of material produced. This testing frequency is recommended in NUREG-1623 and is equivalent to others approved by the staff and have been implemented at other reclaimed sites during construction.

DOE's proposed rock durability testing program will include the following tests, shown with their American Society of Testing and Materials (ASTM) designation:

1. Bulk Specific Gravity - ASTM C 127
2. Absorption - ASTM C 127
3. Sodium Sulfate Soundness - ASTM C 88
4. L.A. Abrasion at 100 cycles - ASTM C 131 or ASTM C 535
5. Schmidt Rebound Hardness - ISRM Method

Based on a review of the proposed procedures, the staff concludes that an acceptable durability testing program has been provided to ensure that rock of acceptable quality will be provided. The testing program was developed using suggested staff guidance in NUREG-1623 and is equivalent to several which were approved by the staff and have been implemented at other reclaimed sites during construction.

4.4.4.3 Gradation Testing

DOE proposes that rock gradation testing for each gradation will be performed a minimum of four times and/or at a frequency of one test for every 10,000 cubic yards of material placed. This testing frequency is recommended in NUREG-1623 and is equivalent to others approved by the staff and have been implemented at other reclaimed sites during construction.

4.4.4.4 Riprap Placement

DOE indicates that riprap will be placed using a computerized placement method where the equipment is calibrated to assure that proper thicknesses of rock are placed. In addition, DOE provided specifications for placement of the rock that will confirm that the riprap layers will be placed to the depths and grades shown on the drawings and that riprap will be placed in a manner to ensure that areas of segregation do not exist. Based on a review of the information provided by DOE, the staff concludes that the proposed procedures are sufficient to ensure acceptable placement of the riprap.

4.5 Conclusions

Based on review of the information submitted by DOE and on independent calculations, the NRC staff concludes that sufficient information has been provided to justify that the erosion protection design is adequate to provide reasonable assurance of protection for 1000 years, as required by 40 CFR 192.

Figure E-8 Example of an Erosion Protection Cover for Uranium Mill Tailings

REFERENCES

DOE, 2009. U.S. Department of Energy, "Phase 1 Decommissioning Plan for the West Valley Demonstration Project," Revision 2, December 2009.

DOE, 2010. U.S. Department of Energy, "Decommissioning and/or Long-Term Stewardship at the West Valley Demonstration Project and Western New York Nuclear Service Center," DOE/EIS-0226, January 2010.

NRC, 2008. U.S. Nuclear Regulatory Commission, "Final Technical Evaluation Report for the Proposed Remedial Action of the Moab, Utah Uranium Mill Tailings Site," Washington, DC, 2008, ADAMS Accession No. ML082060216.

NRC, 2010. U.S. Nuclear Regulatory Commission, "Technical Evaluation Report on the U.S. Department of Energy Phase 1 Decommissioning Plan for the West Valley Demonstration Project," February 25, 2010, ADAMS Accession No. ML100400099.

EWG, 2012a. WVDP Erosion Working Group (EWG), "Recommendations for Phase 1 Erosion Studies," Prepared for U.S. Department of Energy, and New York State Energy Research and Development Authority, July 20, 2012, ADAMS Accession No. ML13072B210.

EWG, 2012b. WVDP Erosion Working Group (EWG), "Erosion Working Group Recommendations for Phase 1 Studies," August 22, 2012, ADAMS Accession No. ML13071A284. http://westvalleyphaseonestudies.org/index.php/public-meeting.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This document provides guidance on conducting technical analyses (i.e., performance assessment, inadvertent intruder assessment, assessment of the stability of a low-level waste disposal site, defense-in-depth analyses, protective assurance period analyses, and performance period analyses) to demonstrate compliance with the performance objectives in Title 10 of the Code of Federal Regulations (10 CFR) Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste." This document provides implementing guidance for amendments to 10 CFR Part 61 that are detailed in the proposed rule, "Low-Level Radioactive Waste Disposal," published in the Federal Register in 2015. The guidance in this document is intended to supplement existing low-level radioactive waste guidance on issues pertinent to conducting technical analyses to demonstrate compliance with the performance objectives. This document provides detailed guidance in new areas that are less covered in existing guidance, such as the inadvertent intruder analysis, defense-in depth analyses, and analyses for the three phases of the analysis timeframe (compliance period, protective assurance period, and performance period). This guidance discusses the use of a graded level of effort needed to risk-inform the analyses for the compliance period (1,000 years), the protective assurance period (from 1,000 years to 10,000 years after disposal site closure), and also covers the performance period analyses that should be performed for analysis of long lived waste beyond 10,000 years. This guidance should facilitate licensees' implementation of the proposed amendments as well as assist regulatory authorities in reviewing the technical analyses. This guidance applies to all waste streams disposed of at a 10 CFR Part 61 low-level waste disposal facility, including large quantities of depleted uranium and blended waste.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)	13. AVAILABILITY STATEMENT
performance assessment, dose assessment, low-level waste disposal, 10 CFR Part 61 compliance, 10 CFR Part 61 performance objectives, time of compliance, period of performance, scenario development, uncertainty analysis, intruder assessment, inadvertent intruder, waste acceptance, site stability analyses, performance period analyses, long-lived waste, depleted uranium, site-specific analyses, technical analyses, concentration averaging, blending, protective assurance period	unlimited
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