Guidance for Conducting Technical Analyses for 10 CFR Part 61

DRAFT Final Report

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NOTE on DRAFT Final NUREG-2175:

On October 18, 2016, the NRC staff met with the Advisory Committee on Reactor Safeguards (ACRS) Subcommittee on Radiation Protection and Nuclear Materials to discuss SECY-16-0106: Final Rule: Low-Level Radioactive Waste Disposal (10 CFR Part 61) (ADAMS Accession No. ML16188A290) that was submitted to the Commission on September 15, 2016. At this meeting, several members requested that the implementing guidance (NUREG-2175) contained herein be made publicly available to support the ACRS full committee public meeting on this issue planned to occur on November 3, 2016. Based on this request, the NRC staff is making this draft final version of NUREG-2175 publicly available in ADAMS. The NRC staff will revise this document and it will be issued as Final NUREG-2175 after the Commission directs the staff on how to proceed on the draft final rule.

The NRC is not soliciting comments on this document because the public comment period is closed and the draft final rule is currently with the Commission for review and approval.

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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, 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 final rule, "Low-Level Radioactive Waste Disposal," published in the *Federal Register* in 2017.

The information 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, such as the inadvertent intruder analysis and analyses for the two phases of the analysis timeframe (compliance 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 or 10,000 years after disposal site closure, depending on the quantities of long-lived radionuclides disposed), and also covers the performance period analyses (beyond 10,000 years) that should be performed for analysis of long-lived waste.

This guidance should facilitate licensees' implementation of the rule 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) the identification and description of defense-in-depth protections; (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 (or a combination of the two); and (4) the development of a safety case for a waste disposal facility.

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PREFACE

The U.S. Nuclear Regulatory Commission (NRC) published the rule, "Low-Level Radioactive Waste Disposal," in 2017. This rule 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). Appendix A of this document highlights changes to 10 CFR Part 61 that were made in the final rule in 2017 and identifies new requirements, particularly relating to technical analyses.

The purpose of this guidance document is to provide licensees with the tools to develop high-quality technical analyses —the performance assessment, inadvertent intruder assessment, site stability analyses, and performance period analyses. This document should also be used by NRC or Agreement State regulators to assist in reviewing these technical analyses. 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. The document provides methods and information the NRC finds generally acceptable to demonstrate the licensee's ability to meet the regulatory requirements.

In addition to the technical analyses, this document covers the process for demonstrating compliance with 10 CFR 61.12(o), identifying defense-in-depth protections, and 10 CFR 61.58, for waste acceptance. Licensees may use this document to assist in identifying defense-in-depth protections, describing their capabilities, and providing a technical basis for their capabilities; and developing the waste acceptance criteria for their disposal sites, as well as for developing acceptable processes for waste characterization and certification.

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 12.0 that defines many of the terms used in this document. This document also includes the NRC staff's responses to public comments received on the draft NUREG-2175 (NRC, 2015c) in Appendix F.

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 inadvertent 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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CONTENTS

DRAFT

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FIGURES

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TABLES

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ACKNOWLEDGMENTS

The NRC staff would like to thank R.L. Johnson and T. Johnson, who were major contributors to the Site Stability Analyses section of this document. Additionally, Adam Schwartzman and Christianne Ridge of the Performance Assessment Branch in NRC were significant contributors to the Performance Assessment Modeling Issues and Inadvertent Intrusion Assessment sections. The NRC staff also appreciates the hazard map figures developed by Allen Gross (Appendix B) and the technical review performed by Karen Pinkston, Tim McCartin, and Michael Lee.

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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 (NRC, 2015a)
BTP WCWF	BTP on radioactive waste classification and wasteforms (NRC, 1983d)
BTP WFTM	BTP on wasteform test methods (NRC, 1991b)
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
OAT	one-at-a-time
OMB	Office of Management and Budget
PA	performance assessment
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

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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, defense-in-depth* protections*,* and waste acceptance to demonstrate compliance with 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).

1.1 Background

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 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. The concepts section (10 CFR 61.7) discusses 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 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 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* means the time from the completion of site closure to 1,000 years after site closure for disposal sites that do not contain significant quantities of long-lived radionuclides. For disposal sites that contain or plan to accept significant quantities of long-lived radionuclides, the compliance period ends at 10,000 years after closure of the disposal site.
>
> *Performance period* is the timeframe established for considering waste and disposal site characteristics to evaluate the performance of the disposal site after the compliance 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 period. 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.

Figure 1-1 provides a visual depiction of the timeframes that are discussed in 10 CFR Part 61 and this document that licensees should consider.

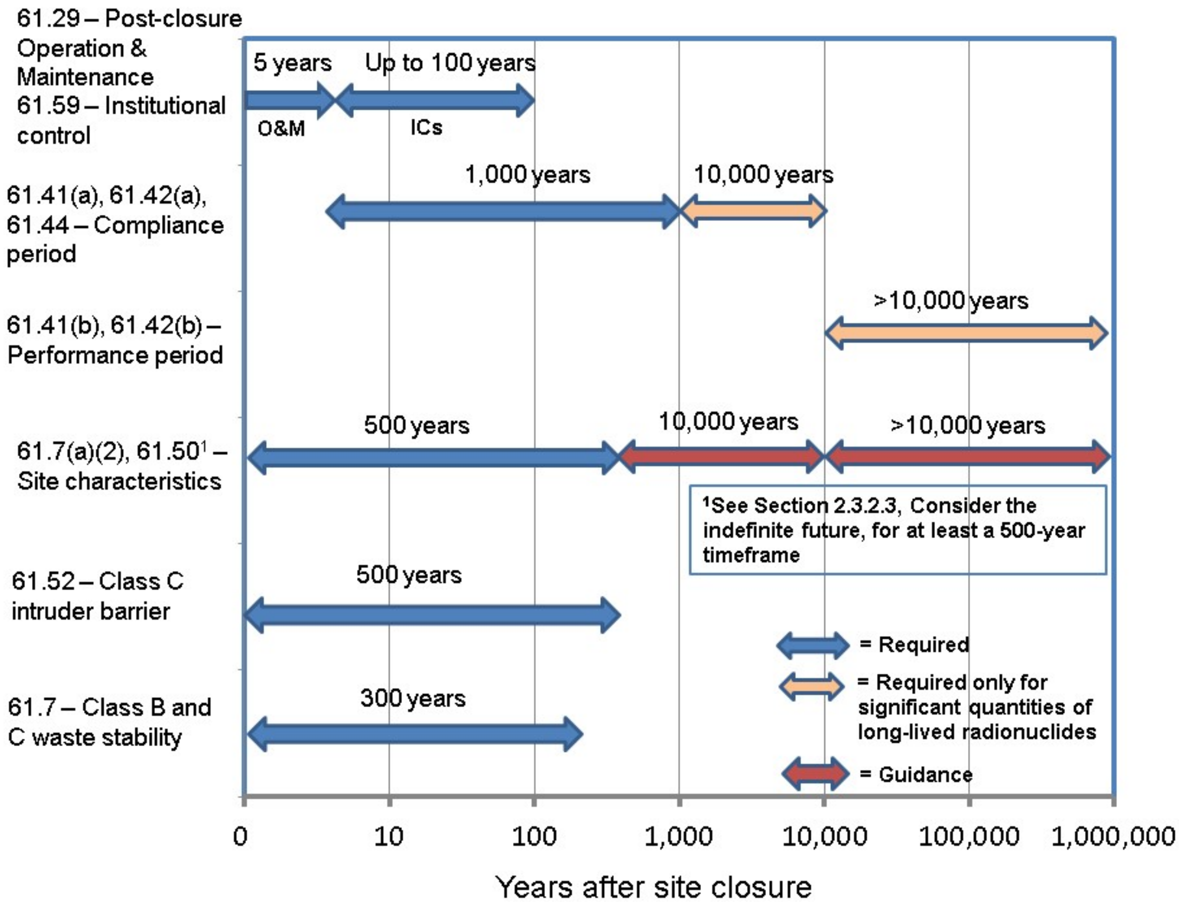

Figure 1-1 Timeframes to be Considered for 10 CFR Part 61

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 *land 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 a description of the safety relevant aspects of the site, the design of the facility, and the managerial control measures and regulatory controls.

As required in 10 CFR 61.10, the information provided in a license application comprises the content of a safety case and must include general and technical information required by 10 CFR 61.11 and 61.12; the technical analyses required in 10 CFR 61.13; and institutional, financial, and other information required in 10 CFR 61.14 through 61.16. Thus, 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 NRC staff provides detailed guidance on the contents of a license application in NUREG-1200 (NRC, 1994). The guidance in NUREG-1200 is supplemented by detailed guidance on conducting the technical analyses in NUREG-1573 (NRC, 2000a) and is updated in Sections 2.0 through 6.0 of this document. Sections 7.0 and 8.0 of this document provide detailed guidance on identifying defense-in-depth protections and describing their capabilities and developing *waste acceptance criteria*, respectively.

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 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 exposures resulting 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. The NRC staff recommends that licensees include a plain language description of the following in their safety case:

- **Strategy for Achieving Safe Disposal of Radioactive Waste**
  The safety strategy should include an overall management strategy for the various activities required in the planning, operation, and closure of a land disposal facility, including siting and characterization, facility and disposal site design, development of the technical analyses, operations, waste acceptance, environmental monitoring, and institutional control. The strategy should describe approaches for managing significant uncertainties to ensure public health and safety is protected.
- **Description of the Disposal Site and Facility**
  The description of the disposal site and facility should describe all the relevant information and knowledge about the disposal system and should provide the basis for the technical analyses. The description should summarize the information required in 10 CFR 61.12.
- **Description of the Technical Analyses Demonstrating Performance Objectives**
  The description of the technical analyses should summarize the performance assessment, inadvertent intruder assessment, site stability analyses, performance period analyses, and analyses of the protection of individuals during operations. These analyses are required by 10 CFR 61.13 to demonstrate compliance with the performance objectives. The description should include key findings of each of the technical analyses including significant associated uncertainties.
- **Strategy for Institutional Control of the Disposal Site**
  The institutional control strategy should summarize the institutional information required by 10 CFR 61.14.

- **<u>Description of Financial Qualifications of the Licensee</u>**
  The description should summarize the financial information required by 10 CFR 61.15.
- **<u>Description of Other Information</u>**
  Depending upon the nature of the wastes to be disposed of and the design and proposed operation of the land disposal facility, the description may need to summarize other information required by 10 CFR 61.16.
- **<u>Safety Arguments</u>**
  The safety arguments should draw together the key findings from the technical analyses to highlight the main evidence, analyses, and arguments that quantify and support the claim that the land disposal facility will ensure protection of public health and safety. The safety arguments should also present an evaluation of uncertainties and any unresolved issues and discuss planned steps to resolve them. The safety arguments should describe additional evidence and arguments that may not have been evaluated in the technical analyses but complement the findings of the technical analyses.

Finally, the safety case for a land disposal facility will evolve over time as new information is gained during the various phases of the facility's development and operation. Therefore, the safety case should be updated as new information that could significantly impact the 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 that includes any updates to reflect final inventory and closure plans. The extent of the final revisions to the safety case may vary depending on the licensee's operation and closure of the land disposal facility and the amount of new information that is developed that could significantly impact safety of the facility.

1.1.3 Defense-in-Depth Protections

Section 10 CFR 61.2 defines defense-in-depth as the use of multiple independent and, where possible, 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 to enhance the resiliency of the land disposal facility. Section 7.0 describes the information that a licensee should provide and a *reviewer* should evaluate with respect to 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 61.12(o) requires licensees to identify defense-in-depth protections, describe their capabilities and supporting technical basis to 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 (e). 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 performance period.

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In this document, consistent with 10 CFR 61.13, the term “technical analyses” comprises the *performance assessment*, *inadvertent intruder assessment*, *site stability analysis*, and *performance period analyses*. A description of each of the analyses is presented in the following sections. The analyses of the protection of individuals during operations required under 10 CFR 61.13(c) is not discussed in detail in this document.

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 the resulting impacts are (Eisenberg et al, 1999). 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 an annual dose to a member of the public.

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 10 CFR 61.41 performance objective for protection of the general public will be met. 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 demonstrating 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) Consider the likelihood of disruptive or other unlikely FEPs for comparison with the limits set forth in 10 CFR 61.41.

(3) 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).

(4) Evaluate contaminant transport *pathways* and processes in environmental media (e.g., air, soil, groundwater, surface water) including but not limited to advection, diffusion, plant uptake, and exhumation by burrowing animals.

(5) Account for uncertainties and variability in the projected behavior of the disposal site and general environment and in the demographics and behaviors of human receptors.

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

(7) If a compliance period of 1,000 years is used, include a technical rationale why a longer time period does not need to be considered in the performance assessment.

1.1.4.2 *Inadvertent Intrusion Assessment*

10 CFR Part 61 regulations envision a period of active institutional controls for up to 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, drilling for water, and 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), an inadvertent intruder assessment must demonstrate that an inadvertent intruder will not be exposed to doses that exceed the limits set forth in 10 CFR 61.42. An inadvertent intruder assessment shall:

(1) Assume that an inadvertent intruder occupies the disposal site and engages in normal activities (e.g., dwelling construction, agriculture, and drilling for water) and other reasonably foreseeable pursuits that are consistent with activities in and around the site at the time of development of the inadvertent intruder assessment. Licensees shall update the inadvertent intruder assessment prior to closure, in accordance with 10 CFR 61.28, to reflect any significant changes to the activities and pursuits occurring in and around the site.

(2) Identify 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 in the projected behavior of the disposal site and general environment.

(4) If a compliance period of 1,000 years is used, include a technical rationale why a longer time period does not need to be considered in the inadvertent intruder assessment.

1.1.4.3 *Site Stability Analysis*

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 "the capability of the disposal site (e.g., wasteform, disposal containers, and disposal units) to maintain its shape and properties to an extent that will not prohibit the demonstration that the land disposal facility will meet 10 CFR 61.41 and 10 CFR 61.42 performance objectives and will, to the extent practicable, eliminate the need for active maintenance after site closure." 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.

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 for the compliance period and that there will not be a need for ongoing active maintenance of the disposal site following site closure.

1.1.4.4 *Performance Period Analyses*

The primary purpose of the performance period analyses is to provide information that demonstrates that releases of *long-lived waste* from a disposal facility are minimized to the extent reasonably achievable. The performance period is defined in the regulations to be the period of time following the compliance period. Performance period analyses are required only if the disposal facility is accepting significant quantities of long-lived radionuclides and the licensee has used a 10,000-year (yr) or longer compliance period. Performance period analyses are not required if the disposal facility is not accepting sufficient quantities of long-lived waste (and consequently is able to justify the use of a 1,000-yr compliance period). The analyses for the performance period may be similar to the analyses performed for the compliance period, but they are not required to be the same.

The disposal system consists of the disposal units, disposal site, land disposal facility, and surrounding environment. The performance period analyses 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.

Section 10 CFR 61.13(e) states:

> If a 10,000 year compliance period is used for either the performance assessment or inadvertent intruder assessment, the licensee shall assess how the disposal site limits the potential long-term radiological impacts during the performance period, consistent with available data and current scientific understanding. The analyses must identify and describe features of the design and site characteristics relied on to demonstrate compliance with the applicable performance objectives set forth in §61.41(b) and §61.42(b).

Figure 1-2 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, inadvertent intruder assessment, and site stability analyses (see Sections 2.3 and 2.5). As shown on Figure 1-2, both the performance assessment and inadvertent intruder assessment are evaluated over the compliance period and the performance period, however, the site stability analyses are only applied to the compliance period. Defense-in-depth is applicable over all time periods and all three analyses types. All of the information contributes to the demonstration that the Subpart C performance objectives are met.

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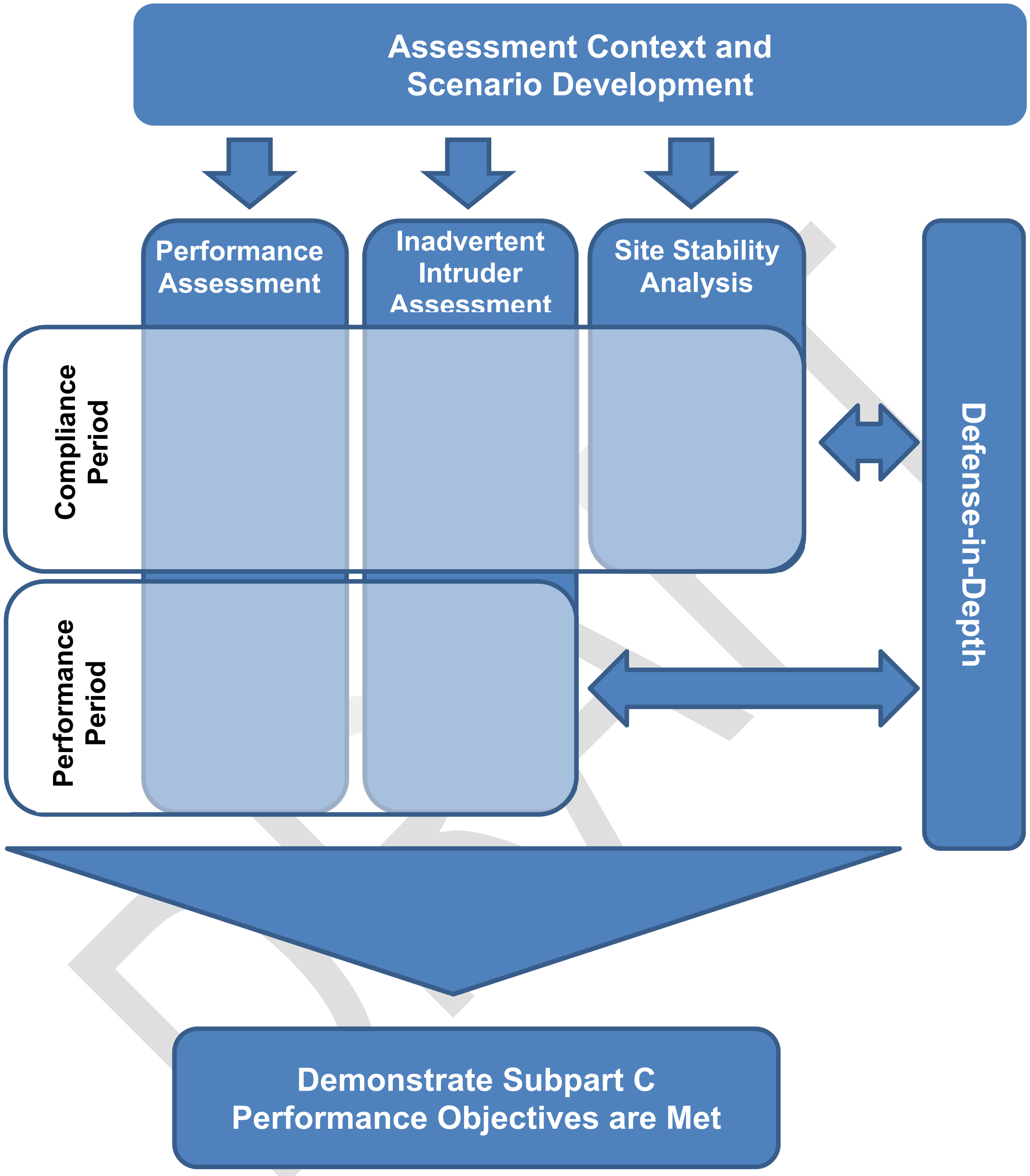

Figure 1-2 Technical Analyses and Defense-in-Depth Relationship to Analyses Timeframes and Performance Objectives

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 the technical analyses required by 10 CFR 61.13 for any land disposal facility, the waste classification requirements set forth in 10 CFR 61.55 for a near-surface disposal facility, or a combination of the results of the technical analyses and the waste classification requirements for a near-surface disposal facility.

Licensees must also identify acceptable methods for characterizing the waste for acceptance. The methods shall identify the characterization parameters and acceptable uncertainty in the characterization data. 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:

- Designate authority to certify and receive waste for disposal at the land disposal facility.
- Provide procedures for certifying that waste meets the waste acceptance criteria.
- Specify documentation required for waste acceptance, including waste characterization, shipment, and certification.
- Identify records, reports, tests, and inspections that are necessary.
- 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 activities. 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.

The need for programmatic technical assistance can arise when the lack of Agreement State resources can impact the Agreement State's ability to maintain a program that is adequate and compatible with the NRC's materials program. Under such circumstances, the Agreement State uses the same mechanism to request special technical assistance to address these programmatic issues. The provision of such assistance will be based on the availability of staff resources and any assistance will be cost-reimbursable. Programmatic issues are 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).

1.1.7 Licensing Process – Documentation and Transparency

Communication, transparency, and clarity are essential to engage the public in licensing decisions. The use of complex, site-specific models has the potential to be a challenge to public involvement; however, steps can be taken (e.g., documentation in plain-language) to alleviate this burden. Regulatory decisions should be as transparent as possible with a clear description of the process and basis for the decisions. The regulator should produce documentation of what was reviewed, what questions (if any) were asked, the resolution of those questions, and the basis for acceptance or rejection of the licensee's proposal. The licensing review documentation should be publically available. The requirement to develop a safety case should help ensure that a plain-language description of the basis for the safety decision is available to the public.

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 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 applicable 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 Sections 10.0 and 11.0 of this document, are available to 10 CFR Part 61 licensees and reviewers for additional 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).

(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. Staff recommend licensees use the information provided in this guidance document over guidance in older documents that is inconsistent with the guidance in this document. Areas where there may be inconsistent information include: 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 document 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

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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) The "Branch Technical Position on Concentration Averaging and Encapsulation, Revision 1," (BTP CA) dated February 25, 2015 (NRC, 2015a), 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." Its primary purpose is to provide acceptable methods that can be used by waste generators, processors, disposal facility operators, Agreement State regulators, and others to perform concentration averaging of specific wastes and mixtures of waste for the purpose of determining their waste class for disposal. It also may prove useful to LLW disposal facility operators in determining site-specific waste acceptance criteria (see Section 8.0). The BTP CA describes voluntary methods that the NRC staff considers acceptable for complying with the regulation in 10 CFR 61.55(a)(8). Licensees may choose these methods or other methods to achieve compliance with this provision in 10 CFR Part 61. In particular, licensees may continue to use the averaging positions in the 1995 BTP CA, if allowed by the appropriate regulatory authority (e.g., the Agreement State regulator of the disposal site) (NRC, 1995b).

(5) NUREG-1757, "Consolidated NMSS Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Criteria, Volume 2, Rev 1," 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.

(6) NUREG/KM-009, "Historical Review and Observations of Defense-in-Depth" was issued in April 2016 (NRC, 2016). It develops principles (i.e., goals) to help guide the implementation of defense-in-depth for the regulated activities for prevention and mitigation of adverse events and accidents. NUREG/KM-009 states the approach used for achieving defense-in-depth is to incorporate multiple layers of defense into the design and operation of the regulated activities and to ensure that these multiple layers address both prevention and mitigation. The guidance contained in NUREG/KM-009 can be used to supplement the guidance in Section 7.0 of this document.

One of the purposes 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 10.0 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:

- acceptable approaches to identify and screen FEPs to develop *scenarios*
- detailed guidance on the analysis for the protection of the inadvertent intruder
- 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
- development of waste acceptance criteria, waste characterization methods, and waste certification
- risk-informing the analyses for the analysis timeframe: the compliance period (1,000 years or 10,000 years, depending on the quantities of long-lived radionuclides), and the performance period analyses (for long-lived waste beyond 10,000 years), using a graded level of effort
- detailed guidance for demonstrating that the proposed disposal facility includes defense-in-depth protections
- discussion of a safety case as a collection of information that demonstrates the assessment of the safety of a waste disposal facility
- discussion of the site closure process and institutional controls
- 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 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 stream (e.g., depleted uranium). 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				
Performance Period Analysis	61.13(e) 61.41(b) 61.42(b)	X	X				X			
Defense-in-Depth	61.12(o)	X						X		
Waste Acceptance	61.58	X							X	
Site Closure	61.12(g)									X

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

The NRC staff has identified methodologies for performance assessment and intruder assessment that licensees can use to demonstrate compliance with 10 CFR Part 61 performance objectives. This 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 provides guidance on the performance period analyses for 10 CFR 61.13(e) associated with the disposal of long-lived waste. Section 7.0 discusses the identification of defense-in-depth protections required under 10 CFR 61.12(o). Section 8.0 discusses the process for waste acceptance, such as developing waste acceptance criteria and performing waste characterization and waste certification. Section 9.0 discusses the site closure process, including conducting performance confirmation to evaluate and verify the accuracy of information used to demonstrate compliance prior to site closure. Section 10.0 provides a cross-walk by performance objective and by topic for the use of other NRC guidance documents. Section 11.0 provides the references cited in this document and Section 12.0 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 could require 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 inadvertent intruder assessment described in Section 4.0 provides methods for risk-informing scenario selection by considering site environmental conditions and

[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).

land use information. The analysis recommended for the site stability analyses in Section 5.0 will ensure that the complexity of the evaluation is commensurate with the *hazard* of the material that will be disposed.

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2.0 GENERAL TECHNICAL ANALYSES CONSIDERATIONS

The term “technical analyses” refers to the performance assessment, intruder assessment, site stability analysis, and performance period analyses needed to demonstrate compliance with 10 CFR Part 61 Subpart C performance objectives. 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 analysis, and performance period analyses. For example, quality assurance, data adequacy, uncertainty, and model support are important with respect to the all of the technical 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.

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) 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 analysis 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 6.0 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.

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, uncertainty identification and assessment, 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, a licensee can develop conceptual models that are implemented as *numerical models*. 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[1].

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

Process is a 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.

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 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 but will include disruptive processes.

[1] Section 12.0 presents a glossary of terms for the whole document.

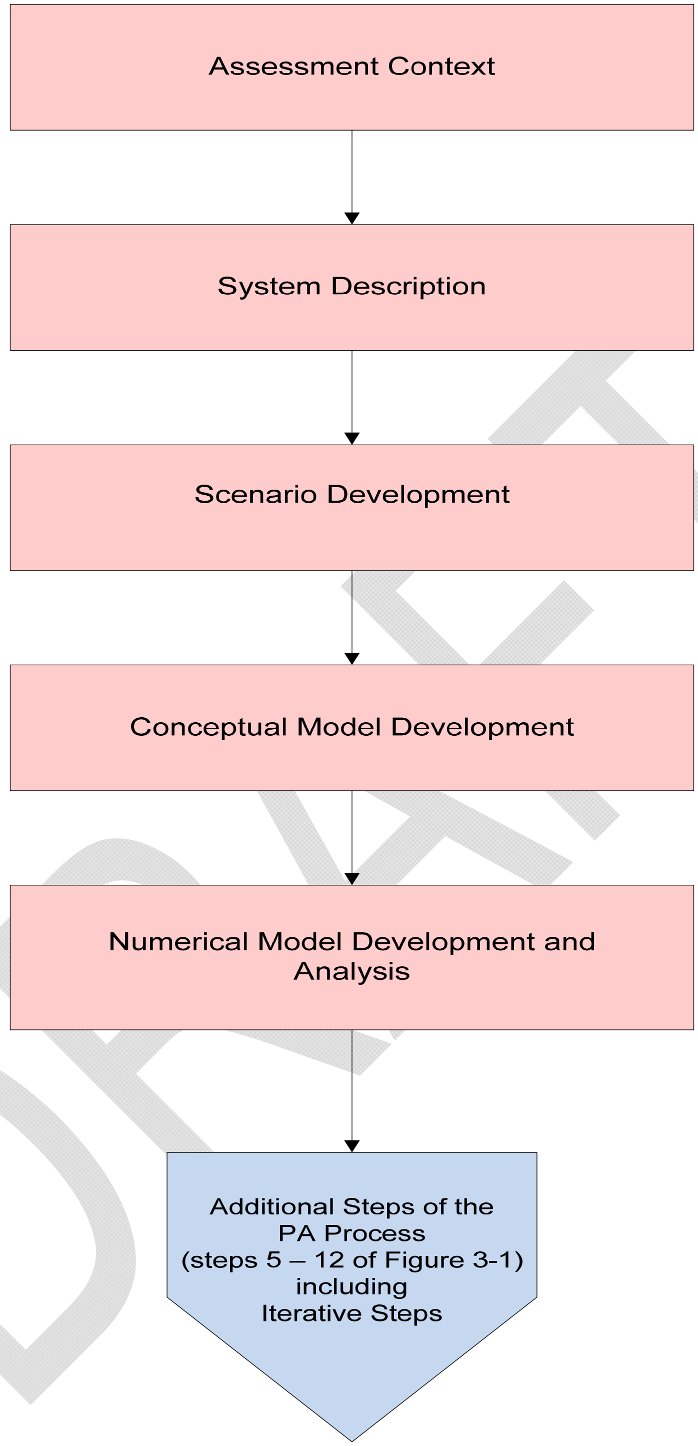

Figure 2-1 Initial Steps of the Performance Assessment Methodology

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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 the behaviors and activities of the people who may be exposed to radiation.

Safety function is defined 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 disposal 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 10 CFR 61.41(a) performance objective, the radiological risk is usually a result of 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. DU that contains significant quantities of long-lived radionuclides may pose a long-term risk to the public due to the ingrowth of progeny.

A licensee should use a level of effort for technical analyses commensurate with the risk to the public from the disposed 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 level of detail of a FEPs analysis associated with disposal of LLW containing predominantly 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

This section provides general review considerations as well as the main elements of quality assurance (QA) associated with technical analyses. Quality assurance for technical analyses is a subset of QA applied to LLW disposal. Additional discussion of QA associated with numerical models is provided in Section 2.7.1.

2.2.1 Quality Assurance for Technical Analyses

Quality assurance, in the context of LLW disposal, comprises all of the planned and systematic actions necessary to provide adequate confidence that the applicable regulatory criteria will be met. An adequate QA program is essential to ensuring that the information relied upon to make LLW disposal licensing decisions is correct and accurate. A licensee is required in 10 CFR 61.12(j) to provide a description of the QA program, tailored to LLW disposal, developed and applied to:

(1) the determination of natural disposal site characteristics;
(2) the development of technical analyses required in 10 CFR 61.13; and
(3) quality assurance during the design, construction, operation, and site closure of the land disposal facility and the receipt, handling, and emplacement of waste.

This section provides updated guidance on QA with respect to the development of the technical analyses required in 10 CFR 61.13. Guidance on items (1) and (3) is provided in NUREG-1200, Rev. 3, “Standard Review Plan for the Review of a License Application for a Low-Level Waste Disposal Facility” (NRC, 1994). Additional resources are provided in Appendix I of NUREG-1757, Volume 2 (NRC, 2006), in which regulatory guidance pertinent to QA is applied to decommissioning sites; NUREG-1293, Rev. 1, “Quality Assurance Guidance for a Low-Level Radioactive Waste Disposal Facility” (NRC, 1991c); and Sections 4.4 and 8.0 of NUREG-1854 (NRC, 2007a).

The main elements of an overall QA program are:

- management systems
- assignments of responsibility within the organizational structure

- training and qualifications
- procedures
- document control
- audits and surveillance
- corrective actions

Quality assurance applied to technical analyses will be a subset of the overall QA program applied to the LLW disposal facility. The elements of QA for technical analyses may include:

- graded approach
- data quality
- development of scientific and engineering software
- software evaluation
- technical review
- transparency and traceability
- technical documentation

The review of QA for technical analyses should verify that the licensee has applied QA measures to the initial development and the updating of technical analyses.

2.2.1.1 *Graded Approach*

A graded approach based on the hazard and risks associated with the waste may be used to review the QA information provided by a licensee. The adequacy of QA measures may be determined using a sample of analyses selected based on their risk significance, and conclusions may be based on impacts of any identified deficiencies on performance. For example, a QA deficiency of a risk-significant element of the performance assessment may have a minor, moderate, or major impact on the results of the analysis. The reviewer should consider both the severity and the pervasiveness of deficiencies when evaluating the adequacy of a licensee's QA measures.

2.2.1.2 *Data Quality*

Technical analyses, such as performance assessments, may rely on hundreds of data inputs or more. Data inputs can be obtained from a variety of sources that may have differing degrees of qualification applied to them. Ideally, the data inputs that a licensee uses in their technical analyses were obtained or qualified under an "acceptable" QA program, such as, but not limited to, an NRC-approved QA program developed to meet the requirements of 10 CFR Part 50, Appendix B.

In some cases, not all the data used in a performance assessment has been qualified. At a minimum, data must be documented and identified in a manner that facilitates determination of the qualification status (qualified, unqualified, accepted) of the data. Regardless of the qualification status of the data, the validity of the data for use in the technical analysis should be established and documented. If data that is not qualified is used, the validity of the data should be established by the licensee for use in the technical analyses.

The validity of qualified data is established through a qualification process, including the following:

- If data are not collected under an "acceptable" QA program, the data should be verified by one or more of the following processes: a QA program that is equivalent to an NRC-approved QA program (e.g., per 10 CFR Part 50, Appendix B), comparison to corroborating data, confirmatory testing, or peer review (NRC, 1988a).
- Data obtained from literature sources such as journal articles, NUREGs, and other similar technical reports should reference their original source.
- Any modifications to the data should be described.
- The units of the data should be provided.
- The representativeness of the data for the site-specific application should be provided; temporal and spatial variability should be considered.
- The appropriateness of the data for the scale of application should be provided.
- The technical basis (e.g., statistical basis) should be provided to support the identification of data values as outliers.

Many data inputs will not have a significant impact on the results of the technical analyses. It is common that less than ten parameters out of many hundred data inputs may explain the total variance in the results. Confidence should be high in the validity and representativeness of the most important parameters.

2.2.1.3 *Development of Scientific and Engineering Software*

Licensees should ensure that the software they use is in conformance with the active standards of the IEEE Standards for software development, quality assurance, testing, verification, and validation (e.g., IEEE Standard 730-2014, 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.

Software may need to be developed for the technical analyses or they may be acquired from other sources.[2] The appropriate QA process for developing software may differ significantly from the QA process used when acquiring software for use. Acquired software may include commercially available products, as well as, software obtained from external sources. It is the licensee's responsibility to determine that software is accepted for use. Accepted software is software that has been has been demonstrated to perform intended functions.

2.2.1.3.1 Software Acceptance

Acquired software will need to be evaluated to determine that the software can be accepted and used. Requirements controlling software procurement should be established to ensure proper verification and validation support, software maintenance, configuration control, and performance of software audits, assessments, or surveys. Software acceptance will differ

[2] Models that are developed using commercially available modeling software should be managed similarly to developed software.

based on the maturity of the software and if the software is widely used or not. Mature and widely used software may be accepted as is after completion of installation testing. In some cases, software may have been endorsed by the NRC. Further acceptance testing beyond installation testing is not necessary for NRC-endorsed software. The main elements of software acceptance may include:

- An installation test should be performed on each intended platform and operating system prior to acceptance and release for use. Documentation of the installation testing should be developed that indicates who performed the testing and what tests were performed.
- A copy of the source *code* should be included with the QA documentation unless prohibited by copyright or licensing restrictions.
- A software validation plan should be developed which describes and justifies the approach taken for validation.
- Documentation of the limitations associated with the software should be described.
- Requirements for suppliers reporting software errors to the purchasers and, as appropriate, the purchasers reporting software errors to the supplier are provided.

2.2.1.3.2 Software Development

Software development should be planned, controlled, and documented to establish that the software is validated for use. Planning for validation identifies the validation methods and validation criteria to be used. The licensee should demonstrate that the software adequately represents the processes and systems for which it is intended.

A licensee should apply controls to software to ensure that the software supporting the technical analyses is qualified for use and has been developed, tested, and controlled under suitable conditions. Specifically, the licensee should demonstrate the following conditions are met:

<u>Planning and Development:</u>

- The software development and maintenance process is completed in a planned, traceable, and orderly manner, using a defined software life-cycle methodology.
- A software configuration management system has been established.
- Software requirements documents, software test plans, and software validation plans are used.
- Training on software usage and QA requirements is provided.

<u>Verification, Validation, and Testing:</u>

- Software verification activities were planned, documented, and performed for each item of software.
- Software that was verified and was subsequently changed has undergone additional verification and validation, and documentation of the additional verification and validation has been developed.
- The software performs intended functions, provides correct solutions, and does not cause adverse unintended results.

- A software test plan is developed that will demonstrate the software performs all intended functions. Tests should provide evidence of correct and successful implementation of underlying theory and algorithms and benchmarking or comparative testing against results from other software, if available. The test plan should identify acceptance criteria that specify what constitutes a passing or failed test.
- Software testing is completed by comparison to measurement results, research papers, laboratory experiments, existing test cases, or other published sources of data. In the absence of data, independent peer review may be used. Comparison to the results of other modules may provide an additional line of support.
- Test case or test cases representative of the intended application should be performed.
- A test case typically describes the requirement being tested, the software or module being tested, the test conditions, list of inputs, list of outputs, and expected results.
- Test cases evaluate the stability of the numerical methods and the accuracy of the numerical methods to represent the *mathematical model*.
- When one unit of software or a module is used in combination with other units of software or modules, the testing should verify the correct transfer of information, that the measurement units in the components are consistent or have been converted properly, and the scale of data (temporal and spatial) is consistent or has been converted properly.

<u>Documentation:</u>

- Software requirements documentation defines the objectives, inputs and constraints, operating systems and platforms, user interfaces, and overall structure and flow of information.
- Documentation should be developed that is sufficiently detailed to allow an informed reviewer to follow the logic of software development.
- A User's Guide should be developed that provides installation instructions, discussion of limitations, resource requirements, and installation test cases.
- Test cases and results should be described. The range of inputs included in the testing should be documented.
- Description of mathematical models that are used in the software is provided, including governing equations, formulas, algorithms, and their scientific and mathematical bases.
- A copy of the source code should be included with the QA documentation unless prohibited by copyright or licensing restrictions.
- Errors identified are documented and their impacts are assessed and documented.

2.2.1.4 *Technical Review*

Technical review is an essential element of the technical analysis process. The guidance that follows is applicable to internal technical review completed by the licensee prior to release of technical analyses to stakeholders as well as to regulators reviewing the licensee's technical analyses.

Technical analyses may use software and modules or other calculations (e.g., spreadsheets). The reviewer should assess the analysis to confirm that it was transparently documented, the objective of the analysis is described, accepted software was used, and the software or modules were not used outside of the range of their intended functions. The internal technical reviewers must be technically qualified to perform the review and be independent from the work being reviewed. Specifically, the reviewer should ensure that:

- The objective (intended use) of the software has been provided.
- The description of the conceptual model implemented is clear.
- Software has been used in a manner that is consistent with the conceptual model implemented in the software.
- Identification of inputs and their sources has been provided.
- Assumptions and technical basis for the assumptions are provided.
- Software or models have not been used in a manner that exceeds known limitations.
- Any associated software used, computer calculations performed, and inputs and outputs have been identified and are traceable.
- Discussion of initial and boundary conditions is provided.
- Model limitations (e.g., data available for model development, valid ranges of model application, spatial and temporal scaling) are discussed.
- Software execution is appropriate with the various sources of uncertainties (i.e., conceptual model, mathematical model, process model, system model, parameters).
- If a defect was identified in software that adversely affects the results of previous software application, the condition adverse to quality was documented and controlled.

2.2.1.5 *Transparency and Traceability*

Transparency and traceability applies to data, software, and technical analyses, including all the associated documentation for each. Traceability is the ability to trace the history, application, or location of an item (and like items) or activities through recorded identification. Acceptable traceability means items can be traced without recourse to the data originator. Data should be traceable from original source to final usage, through all calculations and data reductions. Transparency means the ability to easily access and work with data no matter where it is located or what application created it.

The licensee should ensure and the reviewer should confirm that:

- Data are identified in a manner that facilitates traceability from the associated documentation back to the source and clearly identifies the qualification status (e.g., qualified, unqualified, or accepted, such as, for a physical constant).
- Documentation regarding data traceability and qualification is transparent and identifies the principal lines of investigation considered. A document is transparent if it is sufficiently detailed as to purpose, method, assumptions, inputs, conclusions, references, and units so that a person technically qualified in the subject can understand the document and ensure its adequacy without recourse to the originator.

DRAFT

- The data reduction process is described in detail sufficient to allow independent reproducibility by another qualified individual. Data reduction includes processes that change the form of expression, quantity of data or values, or number of data items. Verify that data reduction inputs, outputs, and computational methods are documented.
- Any changes that affect data identification (e.g., category or use/application) are made in a manner that preserves traceability.

2.2.1.6 *Technical Documentation*

The primary objective a licensee should achieve with their technical documentation is to provide a description in sufficient detail such that an independent reviewer can understand the document without recourse to the originator. The technical documentation provided by a licensee should:

- Provide transparency and traceability of data, software, and technical analyses as discussed in Section 2.2.1.5.
- Describe the work in sufficient detail that a qualified independent reviewer can understand the work without recourse to the author.
- List assumptions and the basis for assumptions.
- List references cited.

2.2.2 Data Adequacy

It is important for a licensee to develop and use valid data. The data should be appropriately representative and complete, of adequate quality, and unbiased. There may be some overlap between data quality (see Section 2.2.1.2) and data adequacy. 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 the 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 2.2.3.1.3. The types of data to be considered by licensees may include, but are not limited to:

- site-specific data (e.g., laboratory and field-scale measurements or experiments)
- data from analogous sites
- data from generic sources
- output from detailed process-level models
- 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 only if necessary. When expert judgement is used to assign data values, the data should be assigned appropriate uncertainty, and the expert judgement should be 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 risk significant then the data should be replaced with data from more objective sources.

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.

2.2.3 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.

2.2.3.1 *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

DRAFT

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.

2.2.3.1.1 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 evaluated in the technical analyses by including in the assessment 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 where the groundwater flow pathways remain unchanged (no major climate variation), or 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.

DRAFT

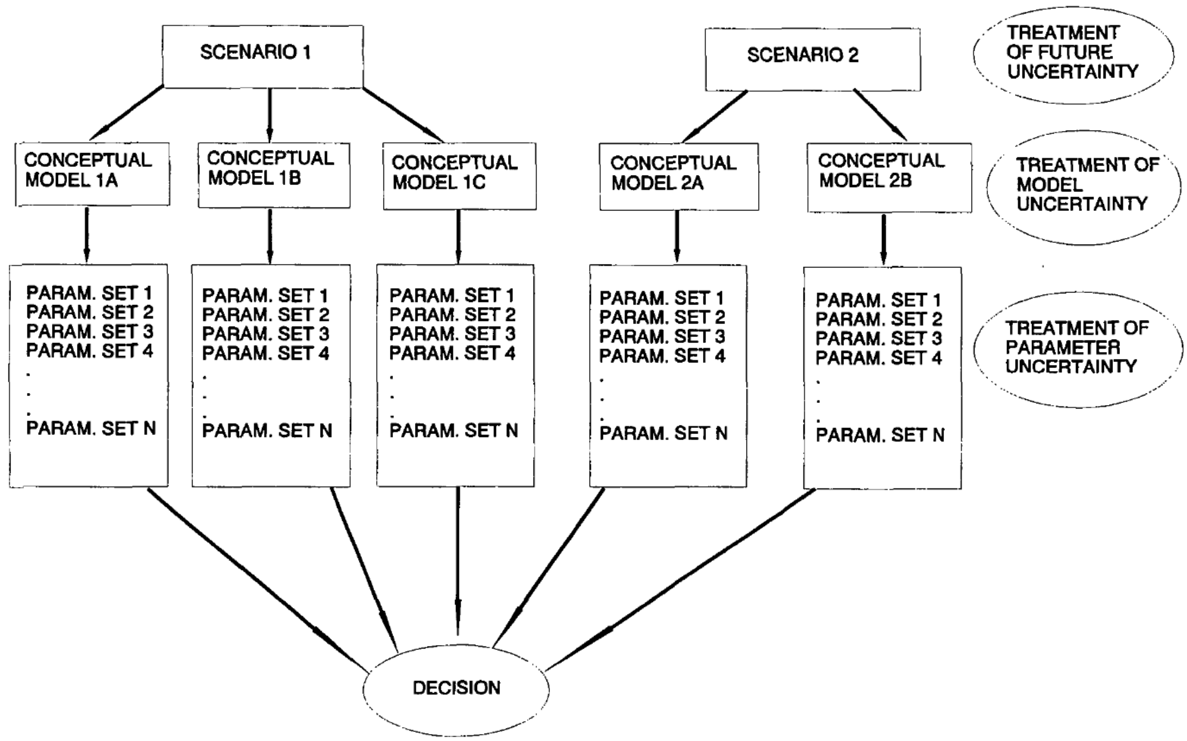

Figure 2-2 Overall Approach to Uncertainty Analysis for LLW Performance Assessment (NRC, 1993a)

2.2.3.1.2 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. Ideally, a licensee can minimize the impact of model uncertainty by developing as much model support as practical (see Section 2.2.4). The licensee can better understand the impact of model uncertainty 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.

2.2.3.1.3 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 essential inputs to any model. Spatial or temporal variations in parameter values are often needed to reflect the evolution of a site and 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 in the outputs, 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 2.2.4. In a *deterministic analysis*, licensees can examine the impact of parameter uncertainty with sensitivity analyses. The licensee can represent uncertainty in the deterministic analysis 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).

2.2.3.1.4 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 sensitivity 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.

2.2.4 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. Inadvertent intruder assessments are based on plausible but hypothetical scenarios. Support for the calculations is essential for effective decision making. 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 under similar conditions and the barriers have similar design and 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 sensitive to the environmental 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 arise from extrapolating the results of short-term tests and observations to long-term performance. Standard approaches to development of natural analogs frequently implicitly assume 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).

2.2.4.1 *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. This section covers the use of experts for review and for developing information to support technical analyses. NUREG-1563, "Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program," 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 effectiveness and reliability. 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 most value. Otherwise, the input is may be 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. 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).

2.2.4.2 *Model Support Example –Engineered Cover Performance*

The following example illustrates the type of effort that may be necessary 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

DRAFT

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.

2.2.5 Documentation

Communication, transparency, and clarity are essential to engage the public in licensing decisions. As discussed in Section 2.2.1.5, transparency and traceability should be applied to technical analyses (e.g. documentation, calculations, data). The primary standard for documentation is to provide sufficient detail such that the analyses can be understood without recourse to the originator of the documentation. There will be different backgrounds and education levels of the various stakeholders. The safety case should be documented using plain language that will be understood by a broad audience while preserving the pertinent technical details. The requirement to develop a safety case should help ensure that a plain-language description of the basis for the safety decision is available to the public.

Technical documentation should clearly state assumptions, limitations, and conditions. Data should be identified and the source of the data provided. Use of data tracking numbers is a good practice that can address some QA issues associated with data and provide transparency and traceability. Source references (i.e., those from which the data or information originated) should be provided. Regulatory requirements should be presented.

In general, documentation supporting licensing decisions should be publically-available. This includes the licensee's information and the regulator's review of the licensee's information. References should be provided. If restricted by copyright or other limitation a source to where the reference can be obtained should be provided. The NRC understands that the use of

DRAFT

complex models has the potential to be a challenge to public involvement; however, the licensee should attempt to alleviate this burden. Regulatory decisions should be as transparent as possible with a clear description of the process and basis for the decisions.

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 found in 10 CFR Part 61, including the performance objectives found in Subpart C. However, the purpose of conducting a performance assessment may vary (e.g., safety decision, resource optimization). 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 data, computational, and model abstraction 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 inadvertent intruder assessment, performance assessment, and site stability analysis for the compliance 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 2.2.3 discusses the types of uncertainties that are commonly explicitly considered in technical analyses by licensees.

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 lower than 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 are unacceptable. The technical analyses supply information to inform decision-makers and the public.

Analyses timeframes are specified in 10 CFR Part 61. For disposal of waste that does not contain significant quantities of long-lived radionuclides the compliance period is 1,000 years and performance period analyses are not required. If the waste does contain significant quantities of long-lived radionuclides, then the compliance period is 10,000 years and performance period analyses are required. When implemented properly, this 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. The analyses timeframes are defined in 10 CFR Part 61 as follows:

Compliance period — Compliance period means the time from the completion of site closure to 1,000 years after site closure for disposal sites that do not contain significant quantities of long-lived radionuclides. For sites that do contain significant quantities of long-lived radionuclides, the compliance period ends at 10,000 years after closure of the disposal site.

Performance period — Performance period is the timeframe established for considering waste and disposal site characteristics to evaluate the performance of the disposal site after the compliance period.

2.3.2.1 *Compliance Period*

Section 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(a), and 10 CFR 61.44) when waste does not contain significant quantities of long-lived radionuclides. Licensees should conduct a performance assessment, inadvertent intruder assessment, and site stability analysis 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.

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2.3.2.1.1 Significant Quantities

The compliance period that should be used is dependent on the type of waste that will be disposed at the site. Waste that does not contain significant quantities of long-lived radionuclides should be analyzed for a 1,000-year compliance period. Waste that does contain significant quantities of long-lived radionuclides should be analyzed for a 10,000-year compliance period, as well as a performance period analysis.

This section provides guidance on how a licensee or regulator may determine if a waste disposal site contains significant quantities of long-lived radionuclides. Other methods may be suitable and will be evaluated on a case-by-case basis. In all cases, a licensee may elect to use the 10,000-year compliance period, regardless of the actual quantities and concentrations of long-lived radionuclides that are expected to be disposed at the disposal facility.

The recommended screening process to determine if a site has significant quantities of long-lived radionuclides is:

1) Inventory-based screening
2) Dose-based screening
3) Site-specific (case-by-case)

2.3.2.1.1.1 Screening Based on Inventory

The first step in determining whether or not a disposal site will contain significant quantities of long-lived radionuclides is consideration of the projected inventory. If a disposal site will not contain any long-lived radionuclides, or will contain very minimal quantities of long-lived radionuclides, then further analysis (i.e., the dose based screening described in Section 2.3.2.1.1.2) is not necessary.

Significance is defined with respect to the protection of public health and safety. Protection of public health and safety is achieved by demonstrating the performance objectives in 10 CFR 61.41 and 10 CFR 61.42 will be met. The performance objective for protection of the inadvertent intruder (10 CFR 61.42) is generally based on more constrained receptor scenarios and is less sensitive to hydrologic and environmental variability compared to protection of the general population from release of radioactivity (10 CFR 61.41). A concentration-based approach using tabular values similar to 10 CFR 61.55 waste classification tables can provide for reliable determination of significant quantities with respect to 10 CFR 61.42. A tabular approach is much more difficult to implement for determination of significant quantities with respect to 10 CFR 61.41. Site-specific design and hydrogeology and potential disruptive processes and events will influence the pathways that are important and the magnitude of risk associated with the different pathways. Therefore, different approaches to evaluating the inventory are needed for 10 CFR 61.41 and 10 CFR 61.42. Screening for 10 CFR 61.41, when a potable water pathway is present, requires the use of two tables (Table 2-1 and Table 2-2), whereas screening with respect to 10 CFR Part 61.42 only requires the use of Table 2-2.

The reduction factors in Table 2-1 are values that the regulator may use as a review tool to evaluate the inventory screening performed by the licensee (i.e., determine significance with respect to 10 CFR 61.41). The regulator would multiply the disposal site-averaged isotopic concentrations listed in Table 2-2 by the reduction factor in Table 2-1. For mixtures of

radionuclides, a sum-of-fractions (SOF) approach should be used (see Example 2.1 through 2.3). If the SOF is below 1, then a 1,000 year compliance period is typically acceptable. If the SOF is above 1, then dose-based or site-specific screening is warranted to determine if the disposal site has significant quantities (see Section 2.3.2.1.1.2 and 2.3.2.1.1.3). Site-specific screening may result in the development of reduction factors that are different, and in general are higher, than those found in Table 2-1. The licensee may still elect to use a 10,000 year compliance period, even if the result of the inventory screening is less than 1.

Table 2-1 Isotopic Reduction Factors for 10 CFR 61.41

Radionuclide	Reduction Factor (unitless)
C-14	0.003
C-14 in activated metal	0.03
Ni-59 in activated metal	1
Nb-94 in activated metal	1
Tc-99	1
I-129	0.0006
Long-lived alpha-emitting nuclides	0.0005
Pu-241	0.0005
Cm-242	0.0005

The generic reduction factors are a conservative approximation but may be a useful review tool and may reduce regulatory burden. The isotopic reduction factors are only applicable to sites where release to groundwater is the dominant exposure pathway. A licensee should use caution when only considering inventory to determine if the site will contain a quantity of long-lived radionuclides that is significant. Whereas the inventory can be a good indication of significance with respect to 10 CFR 61.42 — inventory alone, unless it is very limited, may not be a good indicator of significance with respect to 10 CFR 61.41.

A licensee should compare disposal site-averaged isotopic concentrations to the values provided in Table 2-2. If the disposal site-averaged isotopic concentrations exceed the values in Table 2-2 a 10,000 year compliance period is needed. The table was developed as a screening tool to help determine if a longer compliance period is necessary with respect to providing inadvertent intruder protection. The concentration values in Table 2-2, 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.

Table 2-2 Disposal Site-Averaged Isotopic Concentrations that Require a Longer Compliance Period

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
Radionuclide	**Concentration (nCi/g)**
Long-lived alpha-emitting nuclides	10
Pu-241	350
Cm-242	2,000

During the original development of 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). The NRC staff decided to reduce this variability when deriving the 10 nanocuries per gram (nCi/g) concentrations 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 the NRC staff believes it is appropriate to simplify the consideration of variability. The concentrations provided in Table 2-2 are only to determine if a 10,000 year compliance period is necessary, not to determine compliance with performance objectives.

A licensee should estimate the disposal site-averaged isotopic concentrations of radionuclides to determine if use of a longer compliance period is 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. The material between disposal cells may also be included as long as the disposal cells are located proximally as part of a single disposal facility. 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 2-2 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.

DRAFT

Most disposal facilities are expected to dispose of waste containing a mixture of different isotopes. In order to determine if the disposal facility will contain significant quantities of long-lived radionuclides, a SOF approach may be used. Licensees should estimate the disposal site-averaged concentrations of each isotope. They should divide the resultant values by the concentrations found in Table 2-2 (for 10 CFR 61.42) or the product of Table 2-1 and Table 2-2 (for 10 CFR 61.41) to estimate a fraction for each isotope, and then sum the fractions over all isotopes. If the total is greater than 1.0, then the site will contain significant quantities of long-lived radionuclides and a 10,000 year compliance period should be used. Examples 2.1 through 2.3 provide SOF calculations.

Example 2.1
A licensee wishes to dispose of waste at a disposal site that does not have a potable groundwater pathway or any credible mechanisms for release other than from disturbance by inadvertent intruders. 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 2-2 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 2-2 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, a 1,000-year compliance period can be used and performance period analyses are not required.

Example 2.2

The licensee from Example 2.1 would like to dispose of a new waste stream but they are unsure if they would need to develop performance and inadvertent intruder assessments for a 10,000-year compliance period and 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 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 the 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 2-2). Only one new waste stream is considered, so the equation from Example 2.1 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, a 10,000-year compliance period and performance period analyses are required.

2.3.2.1.1.2 Screening Based on Simplified Dose Assessment

For some sites, inventory-based screening (as discussed in Section 2.3.2.1.1.1) to determine if significant quantities of long-lived radionuclides will be disposed may not be practical or may not yield reliable results. In these cases, screening based on a simplified dose assessment may be necessary.

A key driver of variability in the risk associated with long-lived, mobile isotopes is typically variability in hydrogeology. Though not all sites may have a viable water pathway, most sites do have a viable water pathway. 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), sometimes by a significant margin at certain sites. Depending on the site-specific hydrogeology, these water pathway impacts may occur during the compliance period or during the performance period. For example, the NRC staff previously determined that the isotopes I-129, Tc-99, Cl-36, and C-14 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 is not always correct, particularly for waste classified using 10 CFR 61.55(a)(6) and for long-lived mobile isotopes.

With respect to the demonstration of compliance with 10 CFR 61.41, the concentration of long-lived radionuclides that may constitute a significant quantity may be considerably different at different sites. Significance will be impacted by:

- the dilution or dispersion of releases to an aquifer (e.g., sites with high infiltration and low groundwater velocities) at a site with a potable groundwater pathway
- ingrowth of progeny that increases the radiotoxicity of the waste
- wasteform(s)
- geochemistry of the site
- erosion rates and engineered barrier performance
- gaseous releases from the ingrowth of radon

Site-specific concentration values may be generated by a licensee or regulator, however, it would be difficult for the NRC staff to generate generic point estimate values that would be reasonably accurate for all different wastes, engineered designs, and natural features. To determine if a quantity of long-lived radionuclides is significant with respect to 10 CFR 61.41, a licensee should use iterative screening analyses. Every licensee will have to provide a performance assessment that evaluates an analysis timeframe of at least 1,000 years. The recommended approach builds off of this requirement.

Because the dose screening analyses will be used to determine if a 10,000-year compliance period should be used, the dose screening should be reasonably conservative. A reasonably conservative dose screening analysis is not a worst case evaluation; rather it is an evaluation where credit is assigned to the more robust long-term phenomena. A licensee does not need to provide technical basis if they elect to be more conservative. If the dose screening analyses

becomes very complex in order to determine if the site will contain significant quantities of long-lived waste, the licensee should abandon the screening analyses and should use a 10,000-year compliance period. In addition, for those sites located in Agreement States where the State regulations already require a 10,000-year or longer compliance period, dose screening analyses are not necessary.

The dose screening analyses should[3]:

(1) Credit dilution and dispersion in an aquifer.

(2) Credit wellbore dilution.

(3) Use infiltration rates comparable to natural recharge rates.

(4) Account for radioactive decay.

(5) Credit wasteform performance associated with mass transfer limitations.

(6) Consider ingrowth of progeny. If radon is a consideration, buildup of radium and decay in the source term should be ensured.

(7) Not credit differences in expected transport times.

(8) Eliminate performance credit for those engineered features that are not anticipated to provide performance credit beyond 1,000 years.

(9) Evaluate erosion if engineered barriers providing erosion protection beyond 1,000 years are not part of the design.

(10) Utilize the same exposure pathways as considered in the 1,000-year compliance period evaluation.

Dose screening analyses should not be a significant burden to develop. They are to be developed from the existing analyses that a licensee already has in place. For licensees that have evaluated site characteristics beyond the compliance period when developing their performance assessment of their site, the simplest approach to performing the dose screening analyses is to extend their performance assessment to 10,000 years, reducing credit for engineered features where performance past 1,000 years cannot be demonstrated. Because the licensee evaluated site characteristics beyond the compliance period, there should not be new FEPs that need to be evaluated in the performance assessment for the post-1,000-year timeframe.

[3] Each item should only be considered if it is applicable for the site-specific application being considered.

Example 2.3

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 radiological dose from the waste streams being disposed is dominated by 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 SOF on a disposal site-averaged basis is ≤ 0.5 of the Table 2-2 values. However, because the concentrations of some of the long-lived isotopes are above the product of the Table 2-1 and Table 2-2 values and the hydrology of the site does not provide for significant dilution, the licensee develops 10,000-year compliance period calculations. The compliance period calculations show that 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. The inadvertent intruder assessment shows that potential impacts to intruders are well within the established limits. Because a 10,000-year compliance period was used, the licensee develops performance period analyses to demonstrate that 10 CFR 61.41(b) 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.

2.3.2.1.1.3 Site-Specific Screening

Licensees may propose, and the regulator may approve, site-specific screening to determine if the longer compliance period (i.e., 10,000 years) is necessary. Some disposal sites may have unique pathways of potential release and atypical disruptive processes. The unique characteristics of the disposal facility may make the use of screening based on releases to groundwater pathways unsuitable. In addition, the reduction factors generated in Table 2-1 may be overly conservative for a particular disposal facility. The site-specific screening should follow the general principle that the screening should be clearly conservative and relatively simple. If the screening process is very complex, then the licensee should select a 10,000 year compliance period.

2.3.2.2 *Performance Period*

The performance period is the time after the compliance period when longer-term doses could result from the disposal of significant quantities of long-lived radionuclides. The performance period begins at the end of the compliance 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. The

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objective of analyses provided for the performance period is for a licensee to demonstrate that releases from long-lived waste disposed 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 fluxes to the environment. The long-term performance period analyses are designed to complement the technical analyses performed for the compliance demonstration.

As described in more detail in Section 6.0, 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 performance period that demonstrate that 10 CFR 61.41(b) and 10 CFR 61.42(b) performance objectives will be met. The licensee should use available data and current scientific understanding to assess the performance of the waste disposal facility, including uncertainties.

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[4] considering uncertainty. 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 the disposal of significant quantities of long-lived radioactive waste. 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 6.0 provides more detail on specific technical issues that may be relevant to technical analyses for the performance period.

2.3.2.3 *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 regulatory objective.

[4] As discussed in Section 6.0, the performance period analyses may include metrics other than dose (e.g., concentration, fluxes). See Section 6.0 for more detail.

For the disposal of any type of waste, the hydrological site characteristics identified in 10 CFR 61.50 are required[5] for the next 500 years. For example, disposal should not be 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 10 CFR 61.50 criteria.

Whether a licensee's consideration of site characteristics needs to be extended to the end of the compliance period (i.e., 1,000 or 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 Table 2-2, then apply the sum of the fractions rule for mixtures of radionuclides described in 10 CFR 61.55(a)(7). In this context for considering site characteristics, a minimum quantity is defined as the product of volume and concentration of waste that corresponds to a SOF of 0.1.

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

A) $C < 0.1 \Longrightarrow$ evaluate 500 years

B) $0.1 < C < 1 \Longrightarrow$ evaluate 10,000 years

C) $C > 1 \Longrightarrow$ evaluate performance period

where C is the actual or projected disposal site average waste concentration SOF for long-lived waste (see Example 2.4). As discussed in Section 2.3.2.1.1.1, the calculation of disposal site average waste concentration includes the waste, disposal units, backfill materials, and materials between disposal units but does not include the buffer zone. It is to include the activity in the waste at the time of disposal, but account for peak concentrations resulting from decay/ingrowth for those short-lived isotopes that produce long-lived alpha emitting progeny. By providing a value for long-lived alpha-emitting radionuclides in Table 2-2, 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 2-2 (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.

[5] 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.

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Example 2.4
A licensee performs analyses of a potential disposal site for disposal of waste with characteristics described in Example 2.1. The licensee had calculated the SOF for the waste as 0.223 and determined that a 1,000 year compliance period was required. The licensee uses a period of 500 years to evaluate site characteristics, but wonders if he needs to evaluate further.

Conclusion: Because the SOF was above 0.1 but less than 1(see item B above), the licensee should consider a period of 10,000 years when developing the site characteristics. In general, the timeframe of consideration for developing the site characteristics should be comparable to or longer than the compliance period being evaluated. The regulator should ask for additional information to support the development of site characteristics for the disposal site.

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
- 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 (see Section 2.5.3 for more detail). The bottom-up approach involves the identification, categorization, and systematic screening of FEPs. The bottom-up approach is commonly used for complex sites. The top-down approach uses analyses such as a *safety assessment* and the identified safety functions to develop scenarios. Both approaches may be iterative.

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 can be somewhat blurred. 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 2.5.4.2.

A *safety function* is defined 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, licensees will exclude certain phenomena from the base case performance assessment based on the scenario development process but will include the phenomena in “what if” scenarios. These “what if” scenarios include scenarios of varying likelihood – some may be plausible whereas others are extremely unlikely – and may originate from specific concerns expressed by stakeholders. The “what if” scenarios may include scenarios that would normally have been rejected in a scenario development process due to very low probability of occurrence or low impact on the results. If stakeholder interest is very high, scenarios or conceptual models that are usually excluded by a licensee during the scenario development process could still be included in the performance assessment analyses. However, the interpretation of the results may be difficult since it is not clear which results are realistic and which ones are very unlikely. Therefore, it is generally recommended that licensees avoid “what if” type scenarios and complete the 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. A formal process 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
- 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 or performance period, taking into account the proposed inventory for the disposal site.

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 that will allow a licensee to 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 2.5 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 a more refined 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 at the assessment of a new facility.

Example 2.5: 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 transport 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 volumes or concentrations of waste 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 ensured 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 an 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 external experts. 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 Laboratories 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. 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 is 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. 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 2.5.4.3 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 decision makers, unless the dose projections resulting from the evaluation of disruptive events are below regulatory limits. Section 2.2.4.1 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 specify some individual FEPs 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
- classifying according to scientific discipline

2.5.3.1.1.2 Identification and Categorization of Future FEPs

In the previous section, the NRC staff suggests that a licensee could develop the initial FEP list by assuming the proposed disposal site is not intrinsically dynamic. However, the NRC staff recognizes that most proposed disposal areas are dynamic. 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.

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. Processes considered should include degradation, deterioration, and alteration processes that are expected to occur during the time period of interest. These processes may include chemical and physical degradation (e.g., fracturing/cracking) of a cementitious waste form, corrosion of rebar within vault barriers, chemical and physical deterioration of a high-density polyethylene component of an engineered surface barrier, alteration of the soils on top of an engineered surface barrier, or changes in the groundwater bearing media (e.g., dissolution of limestone causing decreasing travel times). The analyst or *qualified specialist* should 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.

A licensee can identify future FEPs through a qualitative exercise, such as literature searches using qualified specialists. A licensee does not need to complete original research to identify future FEPs. Examination of past local natural history can 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. The past history of the disposal site can be used by a licensee 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). 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 and different distributions of fauna and flora (e.g., Lake Manly covering Death Valley). If the past environment is considered plausible in the future, the FEPs associated with this past environment should be included by the licensee for categorization.

As discussed for the performance period analyses in Section 6.2, more low-frequency events normally are included in the FEPs list for the performance period than may be included in the FEP list for a 10,000 year compliance 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 dictated by regulation 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 or 10,000 years following closure of the disposal site, and a longer-term performance period 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 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 61.50 requirements.

Site suitability requirements are treated differently in 10 CFR Part 61 depending on the type of characteristic 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 generally not amenable to stability and defensible modeling and assessment.

Screening of FEPs Based on the Requirements in 10 CFR 61.50

> **10 CFR 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 to identify FEPs associated with natural resources (i.e., for natural material currently considered to be a resource and whose range and scope is currently known). If review of the FEPs determines that natural resources of the type described in 10 CFR 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 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 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 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.

<u>*Coastal Areas*</u>
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.

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 1 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 1 million 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.

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 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 or performance period.

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 by a licensee 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. Massive floods could destroy a disposal site located close to the surface and therefore the licensee would be unable to demonstrate that the site stability performance objective (i.e., 10 CFR 61.44) will be met. Potential sites located in areas affected by previous glacial processes 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 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 paleoclimatology, 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. For example, Death Valley is generally dry and waterless, however this valley had been flooded in the past (Lake Manly) and the moisture 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 61.50(a)(4)(iv) becomes the primary focus.

> **10 CFR 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 in the future. Evidence supporting the existence of past groundwater discharge areas, such as calcite deposits or diatomite, increases the likelihood that the disposal area may have groundwater discharge in the future.

> **10 CFR 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 or performance 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 an assessment of 10 CFR 61.50(a)(4)(iii) based on the guidance in NUREG-1200 and NUREG-1199.

> **10 CFR 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,

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 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 for probability-based screening include (EC, 2009a):

- <u>Quantitative methods</u>, 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 greater than a 1 in 10 chance of occurring over a 10,000 year period).
- <u>Qualitative methods</u>, 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 phenomenon 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 are available.

Uncertainty Associated with Probability
The main consideration in the assignment of probabilities to scenario-forming FEPs is uncertainty. 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-year 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 should be considered.

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 calculation to indicate that the associated impact will be insignificant. Consequence screening may be difficult to complete with simple analysis if the problem is complex. Shelf- and cliff-type responses, as well as local

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minima and maxima, can confound interpretation of bounding consequence or other types of significance determinations. Example 2.6 provides an example of a cliff-type response and the way it may affect FEP screening.

Example 2.6: 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 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 or additional modeling or sensitivity analyses may provide insights with respect to the significance of the consequences of FEPs.

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 2-3 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 2-3 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 2-3. FEPs can be screened in (included) or screened out (excluded) 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 2-3. 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.

Whether a FEP is screened in or out is apparent in most of the 16 cases in Table 2-3. 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.

Table 2-3 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
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

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 a 10,000-yr compliance period compared to a 1,000-yr 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 need to be included for the longer period based on this increasing uncertainty. For example, if need be, a licensee may extend 1,000-yr compliance period calculations into the future without modification, provided that the calculations are complete with respect to including key FEPs relevant to the longer timeframe or excluding those FEPs only relevant to a 1,000-yr compliance period. However, for time periods considerably longer than the compliance period, FEPs that have been excluded from further consideration in a 1,000-yr compliance period may not be able to be screened out from further consideration for 10,000-yr compliance period analyses. Potentially significant FEPs may need to be considered during scenario development if disruptive processes are expected to start occurring after 1,000 years or if the cumulative impact from repetitive events over longer timeframes is not included in the shorter timeframe 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. The discussion below only provides a brief description of this approach. Licensees may refer to the sources given in the reference section (Section 11.0) for additional information. Both the top-down approach and bottom-up approach are often used 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 as a function through which a component of the disposal system contributes to safety. Safety functions are the 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 its safety functions
- description of the management system applying to the different phases of facility development
- any other information that support continued development, operation, and closure of the facility

The top-down approach to developing scenarios has been used in previous assessments of HLW disposal system performance. Due to the relatively recent development and application of the approach for LLW disposal (EC, 2009b), fewer 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 structured, traceable, 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.

As introduced in Section 2.5.1.1, scenarios are often assembled and classified based on their likelihood of occurrence (probability) of the FEPs comprising the scenarios. 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 may also be referred to with different terminology such as 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. Altered evolution scenarios describe how disturbances affect the evolution of the system.
- “What if” or residual scenarios are generally considered implausible scenarios or scenarios for which the likelihood cannot be accurately estimated. 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 may use scenarios to evaluate uncertainty related to different plausible future representations of the disposal site under consideration. 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. 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 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) 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
- 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.

2.5.4.2 *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 are required to consider uncertainty in the demographics and behaviors of potential human receptors. Receptor scenarios are used to account for these uncertainties. 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 natural evolution of the climate, and with these changes, receptors and their habits may change. Depending on the number of plausible *exposure pathways*, there may be multiple receptor scenarios associated with a central or alternative scenario. In addition, the receptor scenarios (e.g., residential, farmer, recreational) can differ between the central and alternative scenarios (see example Figures 2-3 and 2-4).

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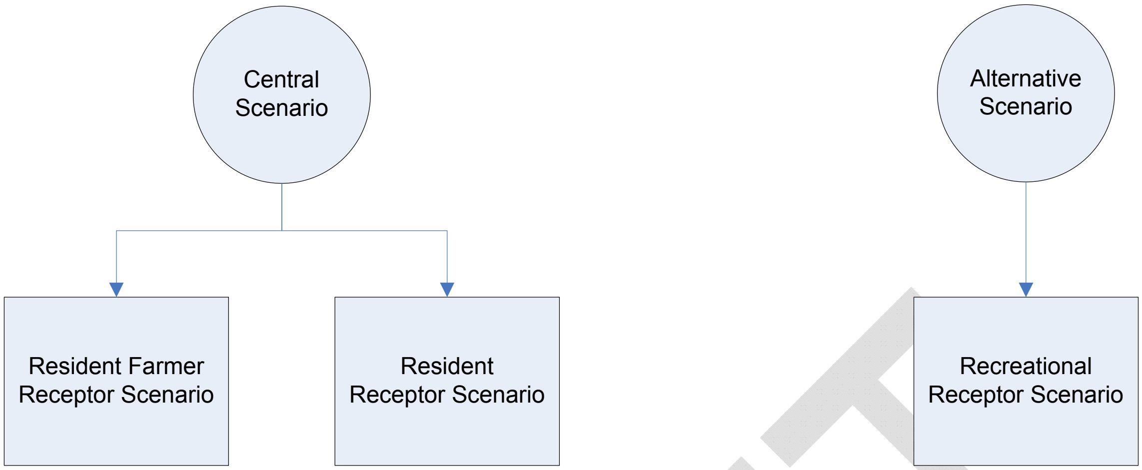


Figure 2-3 A Central Scenario with Several Plausible Receptor Scenarios, and an Alternative Scenario with a Different Plausible Receptor Scenario

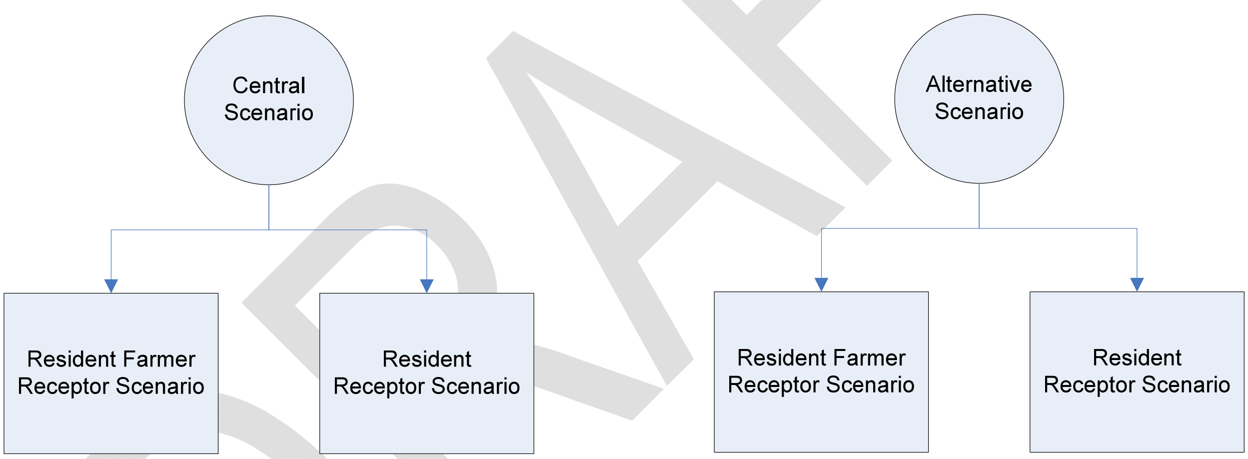


Figure 2-4 A Central Scenario with Several Plausible Receptor Scenarios, and an Alternative Scenario with the Same Plausible Receptor Scenarios

2.5.4.3 *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 4.2 provides guidance with respect to receptors for the intruder assessment. Some of the approaches used in Section 4.2 can be applied in the performance assessment and used to demonstrate compliance with 10 CFR 61.41.

Licensees should estimate potential exposure to the average member of the *critical group* (see Section 3.4.1). 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 inadvertent 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), or they may develop site-specific receptor scenarios. Licensees may develop site-specific receptor scenarios by modifying the exposure pathways included in the generic receptor scenarios or build scenarios 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 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, 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). 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).

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.

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, natural evolution of the climate 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 inadvertent 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 6.0). 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).

2.6 Conceptual Model Development

A licensee should review the information provided for 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 model. Regulators should review simplifying assumptions and determine if an 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 refinement of the conceptual model by a licensee 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 the 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 must be amenable to mathematical representation. The conceptual model must 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 an 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 associated with 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 compared. 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 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 plausible 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 (e.g., it is recommended that licensees avoid "what if" type conceptual models and/or scenarios), 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 or developing software to perform 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[6]

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 staff does not endorse the use of any particular code or modeling software package for analyzing the performance of a LLW disposal site.

A licensee may develop a new model or acquire an existing model. In some cases, a previously developed numerical model may be used, or general purpose simulation software (e.g., GoldSim) may be used to develop a model. This section discusses information relevant to the development of numerical models. Licensees should select a numerical modeling approach that can appropriately represent the site's conceptual model and implement the mathematical

[6] 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.

model. Licensees should ensure that the selected numerical model is developed with adequate QA/QC, as discussed in Section 2.2.1.

Licensees should select a numerical modeling approach that can represent the 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 expressions, 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 represent.

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 but are not limited to 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 (numerical dispersion).

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 2.2.1.3)
- 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 2.2.1.3)

Licensees should provide comparisons between theory and experimental results, field observations, and other supporting information that may involve interpretation and extrapolation (see Section 2.2.4 for additional information on model support). In cases where more than one mathematical formulation may be appropriate, licensees should document why a particular formulation is preferred over other 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 numerical models for waste disposal facilities (IAEA, 2008).

Reviewers should evaluate the numerical models to ensure compatibility with the site conceptual model including the source-term, transport pathways, and receptor scenario(s). 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 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 modeling software, commercially-available or otherwise, or develop software or modeling platforms specifically for site-specific purposes. The modeling may be completed with commercial (proprietary) software, modified existing software, or software specifically developed for the implementation of the chosen mathematical models representing the site-specific conceptual model. Modified existing software and software specifically developed for a site-specific application are referred to in this guidance as “user-developed” software. The use of commercial software has the advantage that the software has been verified and validated during development. Commercial software may have a history of application to a range of different analogous problems. In contrast, user-developed software needs to be developed, verified, and validated by licensees. However, user-developed software does 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 Section 2.2.1.3.

2.7.2 Model Abstraction and Model Simplification

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. Model abstraction 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 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 (e.g., 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 licensee’s 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 information related to these model abstractions.

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

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 licensee should demonstrate that the detail that has been reduced or eliminated by model simplification is not essential to the estimated performance. This can be difficult to do with 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 more complex phenomena. The process of producing simplified models can introduce uncertainties and biases.

It is important that a licensee 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.

A natural tendency of a model developer 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 sensitivity analysis methods work better with a reduction in the number of inputs analyzed by the methods. Model simplification should achieve a balance by preserving essential detail and eliminating unimportant detail.

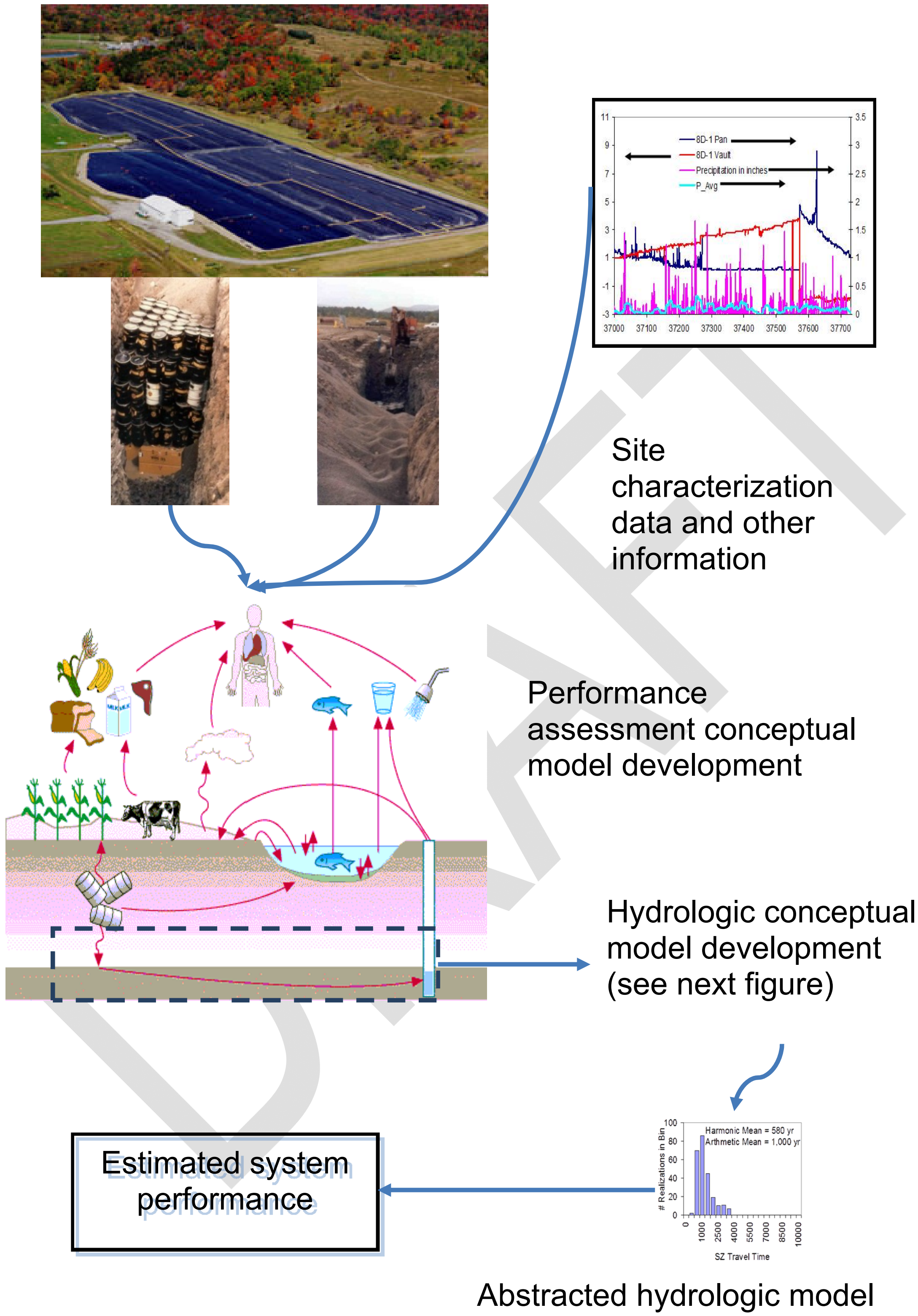
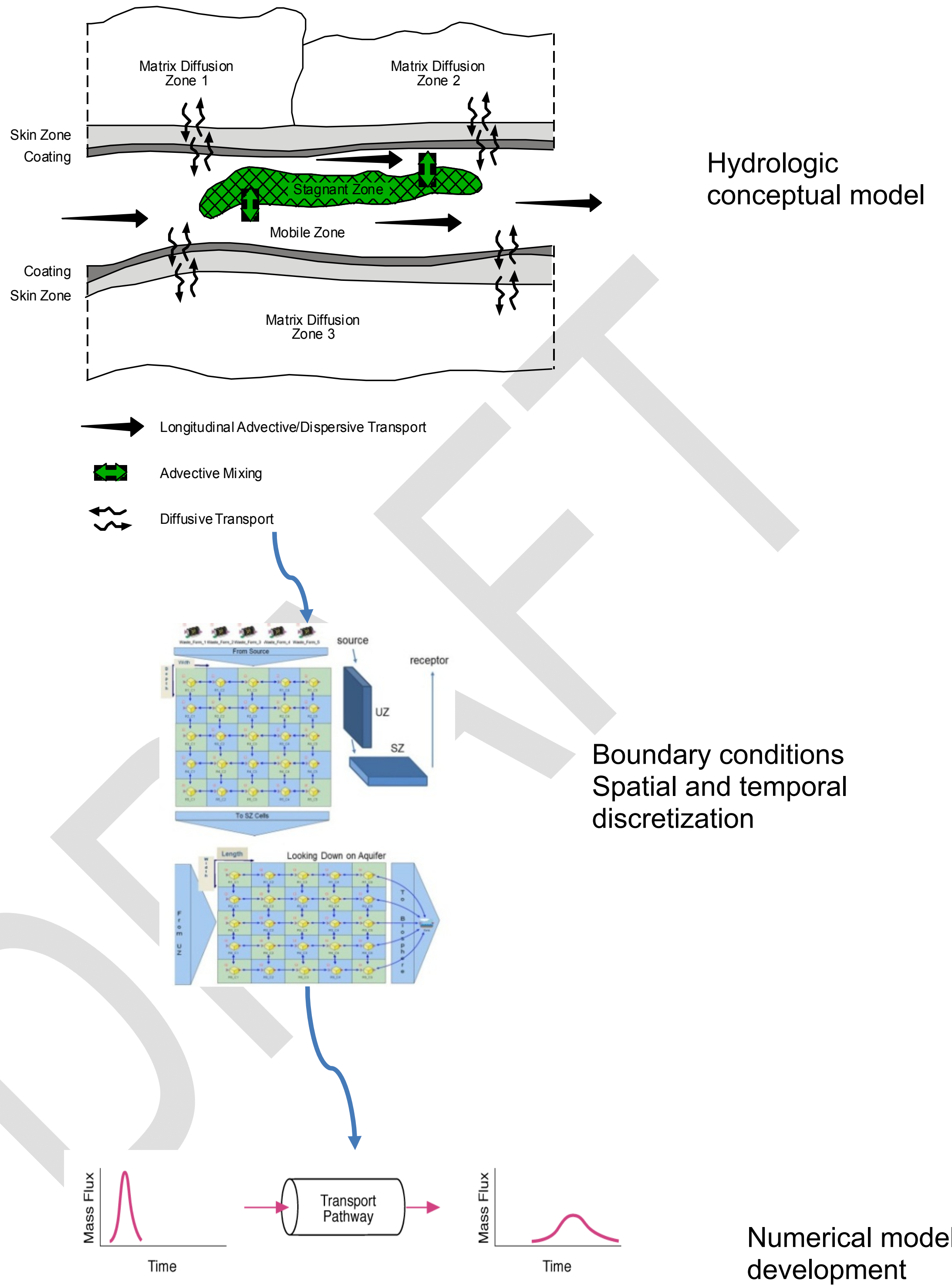


Figure 2-5 Overview of Abstraction as Applied to a Performance Assessment Model



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

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

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 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. Because the models are used to make safety decisions and a central tendency, deterministic model cannot directly include the impact of uncertainty, a conservative representation is warranted. 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 peak of the mean is a protective metric for probabilistic analyses.

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. In addition, a more recent report provides a historical summary of methods used or developed at the NRC (Mohanty et al 2011). Sensitivity analyses may identify the need for additional site characterization to adequately support the technical analyses.

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 in more limited cases, 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 (see Section 6.3.1). 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 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-at-a-time (OAT) 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 of the uncertainty in the parameter. When a licensee must

address multiple uncertainties, assessment of the uncertainties with OAT sensitivity analyses should be avoided because it can lead to misleading results (see Section 6.3.1). In addition, uncertainties should not be relegated to assessment in OAT evaluations; uncertainties that are expected to apply to the system should be represented in the compliance case (base) results. A deterministic approach can be useful 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.

2.7.4.1 *Parametric Uncertainty and Sensitivity Analyses*

This subsection provides a brief listing of the various techniques associated with parametric uncertainty and sensitivity analyses. Information was compiled from a variety of sources including Till and Grogan [Eds.] (2008) and Mohanty et al (2011). This section was written to provide summary information rather than specific direction to licensees and regulators.

The most typical representation of uncertainty is through model input parameters. Represented uncertainties are categorized as aleatory and epistemic. Aleatory uncertainty, also known as variability, refers to the stochastic properties associated with many parameters (e.g., average annual or seasonal stream flow in a stream is well-known, however, difficult to predict for a single specific day in the future). Epistemic uncertainty is the uncertainty in the value of a parameter of a model that is fixed but unknown (i.e., with additional research or field studies the uncertainty could be reduced). This uncertainty can be represented as a distribution of confidence over a range of possible values. A parametric uncertainty analysis allows uncertainty to be properly represented and propagated throughout a model, uses various techniques to exam uncertainties associated with various parameters, and subsequently analyzes its effects on the output results. Natural variability and lack-of-knowledge uncertainty are more frequently being separated in the methods used to propagate the uncertainties through models. For example, Monte Carlo realizations of a model can be used to calculate the effects of both aleatory and epistemic uncertainty in the parameters that determine the model outcome.

The Monte Carlo method involves choosing parameter values using a random, or stochastic, selection scheme. The analysis can be used to sample possible values of parameters from probability distributions. A modified sampling procedure, known as Latin Hypercube Sampling, may be more advantageous because it forces a more even coverage of the sampled space. Convergence of model results to a smooth mean dose curve is important because it is the mean value of the dose that would be compared to the regulations. Depending on the models, a large number of realizations may be needed to reach a smooth, converged result. Additional methods for propagating uncertainty through models besides the Monte Carlo method, include mathematical approximation techniques and analytical methods using mathematical statistics.

Additional components of a parametric uncertainty analysis involve descriptive statistics such as probability distributions that can be described in terms of their functional forms and parameters, their graphical forms, and various descriptive statistics. Probability density function is an example of a probability distribution that describes the likelihood of observing a particular value for a variable across a range and is given the functional representation $f(x)$. A cumulative distribution function is another functional form of a probability distribution and is obtained by

integrating the probability density function. Tolerance levels reflect the uncertainty in the estimates of the mean and variance that are obtained from sampling a distribution.

Due to the lack of data, it may be difficult for a licensee to construct probability distributions for some parameters. Depending on the available data and the assessment of the probable shape, distributions can take many forms such as, but not limited to, uniform, log-uniform, normal, exponential, lognormal, Poisson, triangular, and chi squared.

Correlation among input parameters to a model can have large impacts on an analysis. Correlation in the broad sense refers to any statistical dependence. In common usage it may refer to the statistical relationship between two parameters. Consideration of correlations between parameters can be very important in technical analysis supporting low-level waste disposal. Lack of correlation of parameters may result in non-physical results. For example, if the consumption rates of all food items are represented by probability distributions the total caloric intake may be non-physical in some realizations.

Statistical correlations should be appropriately considered and represented in the analysis. Parameters may be negatively correlated, not correlated, or positively correlated. In some cases more complex statistical relationships may be present. Spurious correlations can sometimes occur. If correlation between parameters is not intuitive, consideration of the potential for spurious correlation should be given. Correlation is not causation and is not a substitute for a proper conceptual model. However, it is normal in the technical analysis process to correlate parameters that may in fact be driven by more complex phenomena that has not been explicitly represented in the analysis. For example, the corrosion rate of carbon steel could be correlated to the infiltration rate because a detailed model for carbon steel corrosion was not necessary to implement in the model.

Confidence intervals are interval estimates of population parameters calculated from observations, but where the interval computed from a particular sample does not necessarily include the true value of the parameter. A 95% confident interval suggests that if the same population is sampled on numerous occasions and interval estimates are made on each occasion, the resulting intervals would bound the population parameter in approximately 95% of the cases. Confidence intervals are a technique to understand the role of sampling error in the averages and percentages that are common in research. Three properties impact the width of a confidence interval: confidence level, variability, and sample size. A larger sample size normally will lead to a better estimate of the population parameter. In applied practice, confidence intervals are typically stated at the 95% confidence level; however, when presented graphically, confidence intervals can be shown at several confidence levels, for example 90%, 95% and 99%.

Parameter sensitivity analysis includes methods used to assess the influence of changes to input parameters on model outputs. Sensitivity analysis provides insights that an analyst can use to refine the model or the model input parameters without devoting undue effort to unimportant areas.

Parameter sensitivity analysis techniques used in the performance assessment analyses are categorized as statistical and non-statistical. Statistically based methods rely on some form of random sampling of input parameters to generate a set of responses from the performance assessment models. They use statistical hypothesis testing to analyze the relationships between the input parameters and the model responses to make inferences about the most

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sensitive input parameters. Analyses can be performed on either the original input set or output value pairs which can be altered by transformations to enhance the sensitivity calculations. Transformations include normalization, rank transformation, logarithmic transformation, scaled-power transformation, standardization, and Gaussian transformation. Because risk is usually based on mean doses, regression results based on transformed variables should be used only on the independent variables. Some non-statistical sensitivity analysis methods are described later in this subsection.

One approach to performing parametric sensitivity analyses is local sensitivity analysis, which measures the impact of a parameter on model output in the region near a specific value. Local sensitivity analysis is used to assess the effect of small perturbations in the value of a parameter around a particular value. Local sensitivity analysis is an OAT technique. OAT techniques analyze the effect of one parameter on a particular function at a time; moving one input variable while keeping others at their baseline or nominal values. They explore changes in a parameter around a particular value, especially when there are many parameters. The amount of insight provided is limited since it does not take into account the simultaneous variation of input variables. This means that the OAT approach cannot detect the presence of interactions between input variables. The OAT approach can only determine local sensitivity and not global sensitivity.

Another relatively straightforward technique is to generate scatter plots of the output variable against individual input variables after randomly sampling the model over its input distributions. The advantage of this approach is that it can deal with a set of arbitrarily-placed data points and gives a simple visual indication of sensitivity. Quantitative measures can also be drawn by measuring the correlations or by estimating variance-based measures by nonlinear regression.

Variance-based sensitivity analysis is a form of global sensitivity analysis, i.e., representing the impact of a parameter across its entire range of values. It is a class of probabilistic approaches which quantify the input and output uncertainties as probability distributions, and breaks down the output variance into parts attributable to input variables and combinations of variables. The sensitivity of the output to an input variable is therefore measured by the amount of variance in the output caused by the input. For example, if a model has two inputs and one output, 60% of the output variance could be caused by the variance in the first input, 15% by the variance in the second, and 15% due to interactions between the two. These percentages are considered measures of sensitivity. Variance-based methods analyze the input space accounting for interactions and nonlinear responses, but are only meaningful when the input factors are independent from one another.

Regression analysis is best used when the model response is linear, which can be confirmed if the coefficient of determination is large. The technique attempts to fit a linear regression to the model response and uses standardized regression coefficients as a measure of sensitivity. Regression methods are based on the correlation between the model results and the independent parameters under the assumption that they are related linearly. Stepwise multiple linear regression highlights those significant input parameters according to how much each input parameter reduces the residual sum of squares. The advantages of regression analysis are low costs and relative simplicity.

Nonparametric sensitivity analyses included the Kolmogorov-Smirnov (K-S) test, the Sign test, and the Wilcoxon Rank Sum test. Nonparametric tests are statistical, but differ from regression tests because they do not require the assumption that the data have normal distributions.

The component sensitivity analysis method looks at the whole performing component, or nonperforming component, of a system at once. Component sensitivity analysis allows the exploration of the resiliency of components that would not be evident unless the other components have failed. Component failure is simulated by changing input parameters to degrade the performance severely either one at a time or in combination with other components allowing interactions as well as redundancy in the system to become evident as selected components are forced to fail.

The strategic partitioning of assumption ranges and consequences method is based on concepts of probabilistic risk assessment (PRA) that aim to extract information on what sets of model parameter values taken together could produce substantially increased doses. The method also determines whether system features, working alone or in combination with other features, maintain their performance even under conditions that are highly unlikely.

The distributional sensitivity analysis can be used to determine the effect of estimation of parameter distributions on the performance results. In this technique, the input distributions can be changed either by shifting the mean of a distribution by a predetermined percentage or changing the shape of the distribution while keeping the minimum and maximum fixed. The distributional analyses can reveal improper choices of distribution functions that can affect the results significantly.

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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 1.1.4.1.

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 (i.e., performance assessment for waste incidental to reprocessing waste determinations) for demonstrating compliance with 10 CFR Part 61 performance objectives, may also be applicable to the development of a performance assessment for a land disposal facility for LLW (NRC, 2007a). Near the end of this document, Table 10-4 provides a crosswalk of various technical topics to other relevant NRC guidance documents.

The following sections provide guidance related to the process for developing a site-specific performance assessment, including technical analyses information that a licensee should provide and that a reviewer should evaluate.

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
(5) an evaluation of uncertainties

The methods of performance assessment should be 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 an annual dose to a member of the public.

The performance assessment may 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 10 CFR 61.41 performance objective. During the design and licensing of a disposal site, assumptions may be made, based on expected waste volumes and compositions, 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 revised information on future waste to be received (see Section 9.0). 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: collecting additional data collection and revising the modeling, modifying the facility, or reducing future waste volumes or specific radionuclide quantities or concentrations (i.e., through setting "allowable" limits, see Section 8.0). 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. Construct reasonably foreseeable scenarios to evaluate for compliance with the performance objective (in Step 5) 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 4.2 for further discussion. Much of the receptor scenario approach used in Section 4.2 can be applied in the performance assessment.
- Step 6: Perform sensitivity and uncertainty analysis — Evaluate which models, assumptions, and combinations of parameters are 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 7.0 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 9.
- 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 much iteration as needed until it can be demonstrated that regulations will be 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). Section 2.0 of this document provides 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 10 CFR 61.41 performance objective for protection of the general public will be met. The results of a performance assessment can be used to support the identification of defense-in-depth protections required in 10 CFR 61.12(o). Licensees may use the results of the performance assessment to quantify barrier capabilities and their associated uncertainties to understand the contribution of the barriers to safety and defense-in-depth.

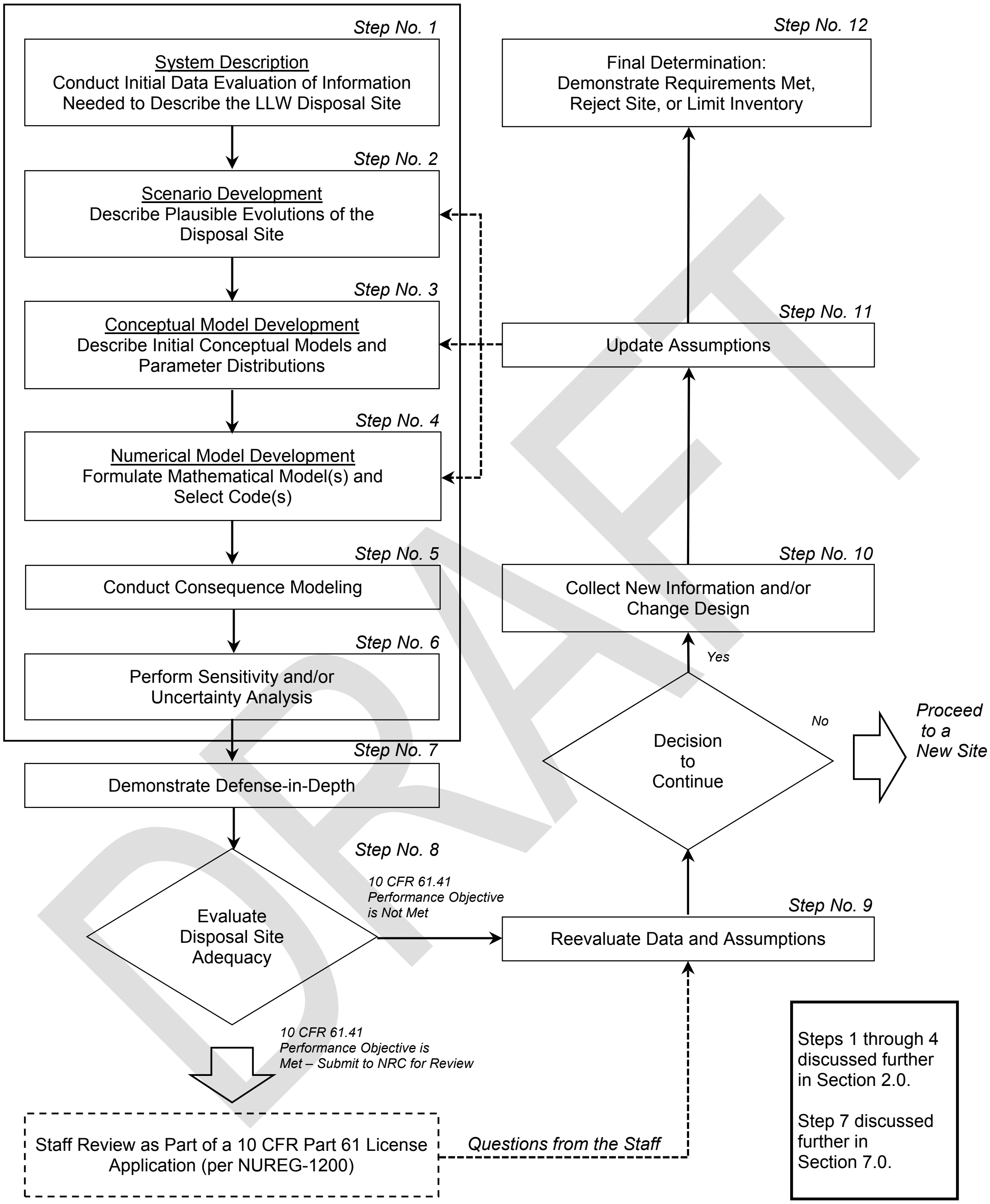

Figure 3-1 Example of a Performance Assessment Process

Section 7.0 of this document provides additional guidance on using the results of the performance assessment to demonstrate defense-in-depth protections are included at a LLW disposal facility.

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 verify 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 site closure application must include a final revision of the safety case and specific details of the disposal site closure plan included as part of the license application submitted under § 61.12(g). The site closure application must also include the results of tests, experiments, or any other analyses relating to backfill of excavated areas, closure and sealing, waste migration and interaction with emplacement media, or any other tests, experiments, or analysis pertinent to the long-term containment of emplaced waste within the disposal site, including revised analyses for § 61.13 and updates to the identified defense-in-depth protections using the details of the submitted site 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 9.3 provides information on mitigation, which might be necessary to continue meeting 10 CFR Part 61 performance objectives. Section 9.2 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 Section 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 10 CFR 61.41(a) performance objective is met and in some cases to support demonstration that 10 CFR 61.41(b) 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 (1) significant credit is taken for some aspect of the source-term modeling (e.g., low *solubility limits*), (2) attributes are relied upon for defense-in-depth protections, (3) higher long-term hazard exists, or (4) 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 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 a case 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. Disposal sites and proposed disposal practices may 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 of the source term significant to disposal system performance
- simulate the behavior of the source term 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.

Sections 2.2 and 2.7 of this guidance document describe 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. A brief description of additional references relevant to wasteforms and waste release is provided in Table 10-5.

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 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, 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. <u>The performance assessment inventory should not be limited to the radionuclides in Tables 1 and 2</u> 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 measurement 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 the 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 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 in the performance assessment modeling or that are relied upon for defense-in-depth protections. Licensees may use sensitivity analyses to identify the importance of geochemical parameters either to identify whether site-specific data should be obtained for significant parameters, or to determine whether the range of values used is sufficient for parameters that do not have a significant effect. Section 2.2.3 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 2.2.4.1). Licensees should carefully select literature values for significant parameters and transparently describe the similarities and discrepancies between the site conditions to which they are proposed to

[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.

represent and the conditions from which the literature values were derived. A reviewer should determine if the 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 container materials may be 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, radiolysis) 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 2.2.4 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, 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 (BTP) on wasteform test methods (BTP WFTM) 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 BTP WFTMapply to cement-based wasteforms and other than cement-based wasteforms.

These elements include:

- qualification testing
- quality of sample preparation
- consideration of variability
- waste characterization
- 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 release and 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 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, a number of key lessons with respect to waste release were identified including:

- 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 resulting 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 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 the tests have been 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

DRAFT

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 2.2.4). 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 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 may be generated in a LLW disposal facility by or from the waste (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 significantly influence 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 intruder 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. 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. By including land management within the scope of management activities, LLW disposal facilities can reduce the impact of biointrusion during the period of institutional control (e.g., limiting vegetation and minimizing the intrusion by animals). 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 greater review effort 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 if it is conservative or if 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.

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Table 3-1 List of Parameters and Processes 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

DRAFT

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 2.2.4, 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. In addition, the spatial variability of the moisture characteristics curve over the area of a disposal site may be unknown.

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 representation 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

DRAFT

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 significant, support for the representation may need to be developed by the licensee 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 to 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.

When release of gaseous radionuclides occurs at the receptor location, atmospheric transport phenomena may have minimal impact. However, the approach to estimating gaseous concentrations may have a significant impact on estimated doses. A common approach is to employ a box model. The box model estimates the average gaseous concentration in the box by estimating the flux rate from the land surface to the air and calculating the mixing associated with the annual average wind speed flowing over the surface into the box. The problem with this approach for calculating gaseous concentrations is that wind speed is highly variable on a much shorter time-scale than the annual averaging period. The highest concentrations in the box are associated with the periods of calm winds and not the periods of highest winds. Integrating short-term wind speed data to estimate average concentrations should be used, or a conservative value should be assigned for annual average wind speed.

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: (1) licensees take credit for significant delay in radionuclide migration via air transport from the disposal facility to the receptor; (2) those that take credit for significant dilution; (3) those that are relied upon for defense-in-depth protections; and (4) 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 use the resultant exposures for comparison with 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 process is often termed pathway analysis. Second, the dosimetry of the exposed individual must be modeled. This step 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 to include in a dose assessment will vary from site to site. A licensee can use a screening process to determine which pathways need to be included in the dose assessment. 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 61.41, 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 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 scenarios.

3.4.1 Average Member of the Critical Group

The term “any member of the public” in 10 CFR Part 61 refers to the receptor for which the dose calculation is performed. The “average member of the critical group” is an acceptable construct to use as the receptor in performance assessments to demonstrate compliance with dose criteria. The critical group is the subset of the population that is most likely to be exposed to radiation. Figure 3-2 provides a conceptual representation (plan view) of the average member of the critical group concept for a hypothetical disposal site. The public is defined as all individuals who are expected to live in the vicinity of the LLW disposal site. Not all individuals will live in a location that could result in exposure to radiation, and furthermore, the points of maximum exposure for individual pathways (e.g., groundwater, air) may not coincide. The critical group would be individuals living at the point(s) of highest concentrations outside the buffer zone surrounding the disposal units. The buffer zone is a portion of the disposal site that is controlled by the licensee and that lies under the disposal units and between the disposal units and the boundary of the site. Generally, the buffer zone is limited to 100 m from the edge of the disposal units. It is acceptable to take a conservative approach and sum the contributions from all pathways, regardless of differences in location. The average member of the maximally exposed group is then used to compare to the radiological dose limits.

The term “any member of the public” is not referring to the hypothetical maximally exposed individual within the population subset. The variability in doses between the critical group and the members of public not exposed to radiation is, in general, much larger than the variability in lifetime doses within the critical group. Considering the unknown characteristics of the future exposure group, this simplification is reasonable and warranted. This approach ensures protection of the general population.

The purpose of the public dose limit is to limit the lifetime risk from radiation to a member of the general public. The conversion factor used to equate dose into risk is based on data from various populations exposed to very high doses of radiation, such as the atomic bomb survivors, and these populations contained individuals of all ages. Therefore, variation of the sensitivity to radiation with age and gender is built into the standards that are based on a lifetime exposure. A lifetime exposure includes all stages of life, from birth to old age. For ease of implementation, the radiation standards, which are developed to minimize the lifetime risk, limit the annual exposure that an individual may receive. The member of the public is not limited by regulation to be an adult, though in many cases, for practical application, it is an adult. The radiological dose is a product of the environmental concentrations, transfer pathways, uptake rates, exposure times, and dose conversion factors. All of these factors must be considered together when evaluating radiological doses. For a common receptor scenario, such as the resident farmer, the exposure times and uptake rates are generally higher than most other receptors. In this case, the adult resident farmer would be the average member of the critical group.

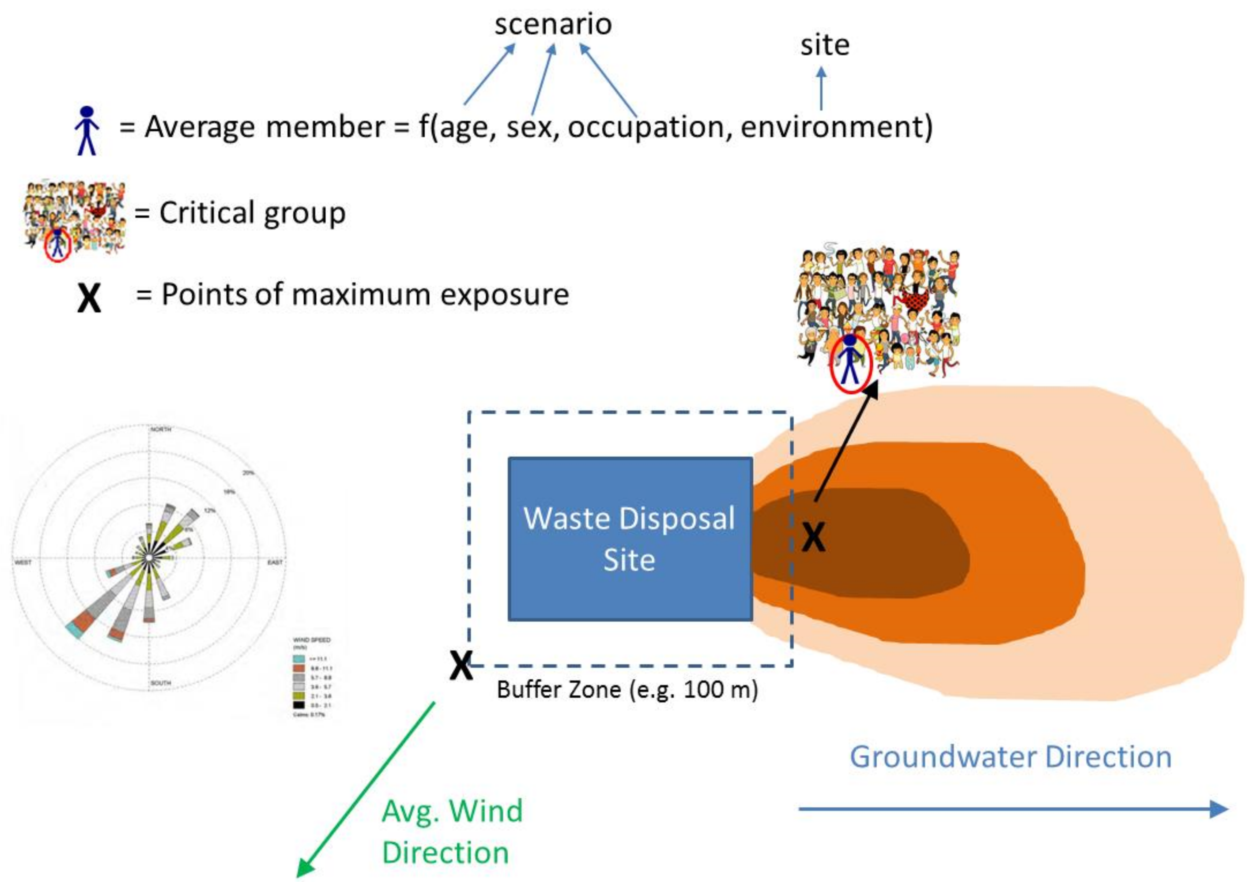

Figure 3-2 Receptor Concepts - Average Member of the Critical Group

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 climate states 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.

3.4.2 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 (e.g., 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 inadvertent 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 inadvertent 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 inadvertent *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), inadvertent 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 through 10 CFR 61.6 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)).[2] 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 inadvertent intruder assessment based on the availability of new dosimetry information, the licensee will need to submit the updated analyses for review and approval, similar to any other update (see Section 9.0). The licensee may need to request an exemption through 10 CFR 61.6 to use the latest dose conversion factors to perform dose analyses for individuals during operations to meet 10 CFR 61.43 performance objective.

[2] 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 through 10 CFR 61.6 from the definition of weighting factor in 10 CFR 20.1003 to use the alternative dose methodology.

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4.0 INADVERTENT INTRUDER ASSESSMENT

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. To demonstrate that the performance objective in 10 CFR 61.42 would be met, licensees must conduct an inadvertent intruder assessment as required by 10 CFR 61.13(b).

The following sections provide guidance related to the process for conducting site-specific inadvertent intrusion assessments, including information that a licensee should provide in their technical analyses and that a reviewer should evaluate.

4.1 Inadvertent Intruder Assessment Overview

The regulations at 10 CFR 61.13(b) require an inadvertent intruder assessment be prepared 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 that might unknowingly expose the person to radiation from the waste included in or generated from a disposal facility, such as agriculture, dwelling construction, and drilling for water, and other reasonably foreseeable pursuits that are consistent with the activities and pursuits occurring in and around the site at the time of development of the inadvertent intruder assessment.

The process for conducting an inadvertent intruder assessment, as shown in Figure 4-1, 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 intruder assessment is an iterative analysis involving site-specific, prospective modeling of potential radiological consequences as a result of normal and other reasonably foreseeable human activities that might unknowingly occur should an individual occupy a near-surface disposal LLW facility after the loss of institutional controls. An inadvertent 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

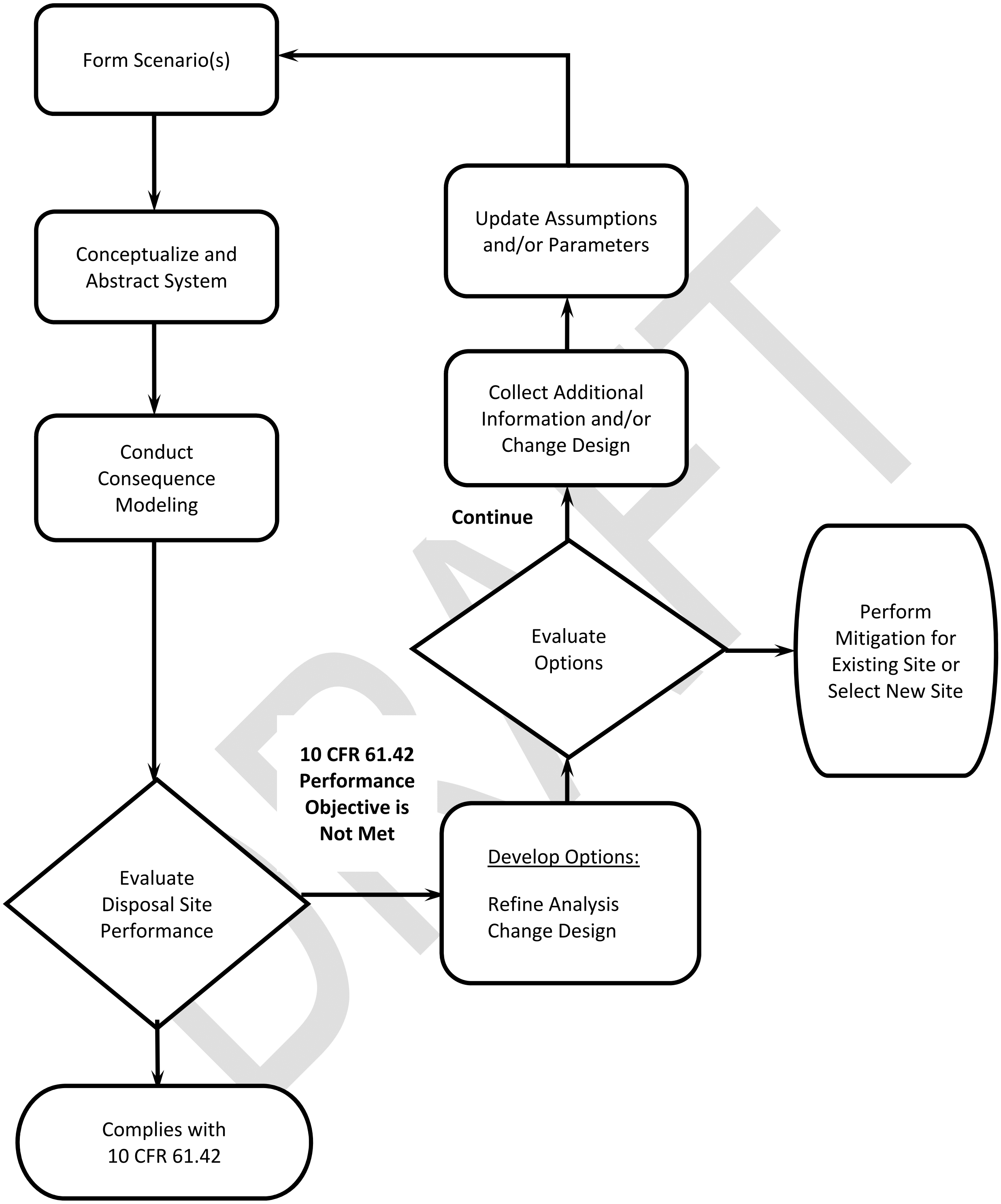

Figure 4-1 Example of an Inadvertent Intruder Assessment Process Required by 10 CFR 61.42

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 ensured and inadvertent intrusion may be possible. Thus, 10 CFR 61.59 provides 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, consistent with recommendations from the NCRP (2005), the assessment assumes that reasonably foreseeable receptor scenarios occur, in which the inadvertent intruder would be expected to receive the greatest exposure to radiation from the waste, in order to demonstrate compliance with 10 CFR 61.42.

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. Inadvertent 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 inadvertent 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 inadvertent 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. Section 8.0 provides 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 inadvertent 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: (i) normal activities, such as agriculture or dwelling construction, which are typical of human pursuits in various times and locations and generally involve the pathways of most concern; and (ii) pursuits that are consistent with

activities in and around the site at the time the inadvertent intruder assessment is developed. Consideration of both normal and reasonably foreseeable activities at the time the analysis is developed 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 compliance period (e.g., the presence of intruder barriers and their degradation, future climate conditions). Section 2.5.3 discusses methods to identify and screen FEPs. These approaches are also generally appropriate for the inadvertent intrusion assessment.

Model abstraction is the process of incorporating the significant FEPs into conceptual and mathematical models that can reasonably describe how the facility limits the inadvertent intruders' radiological exposures. Model abstraction for an inadvertent intruder assessment is similar to model abstraction for a performance assessment. Section 2.7.2 discusses model abstraction techniques for technical analyses in general. These approaches are also generally appropriate for the inadvertent intrusion assessment.

Licensees should use the results of the inadvertent intrusion assessment to identify intruder barriers as well as defense-in-depth protections (see Section 7.0) and understand the uncertainty in the barriers' capabilities. Reviewers should use insights drawn from the review of the inadvertent intruder barriers and uncertainty analyses (see Sections 4.4 and Section 2.2.3, respectively) to focus their review on topics within the inadvertent intruder assessment that are important to inhibiting contact with the waste or ensuring that potential radiation exposures to an inadvertent intruder will meet 10 CFR 61.42 performance objective.

The following sections provide guidance related to the process for conducting site-specific inadvertent intrusion assessments. Section 4.2 provides guidance on forming receptor scenarios for use in the assessments. Section 4.3 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 of this document for guidance on general considerations regarding scenario analysis, model abstraction, and performance assessment that were highlighted in the preceding paragraphs. Section 4.4 provides guidance on information that licensees should include as part of the inadvertent intruder assessment to identify intruder barriers and describe a technical basis for the barriers' capabilities. Section 4.5 describes institutional controls in the context of the inadvertent intruder assessment. Section 8.0 discusses other considerations related to developing waste acceptance criteria from the technical analyses (e.g., using the information from inadvertent intruder assessments to establish site-specific measures to limit radiological impacts if inadvertent intrusion occurs).

4.2 Receptor Scenario Analysis

In developing 10 CFR Part 61, the NRC staff recognized that the presence of institutional controls makes it unlikely, though possible, that an individual will occupy a site after closure. While 10 CFR Part 61 specifies that licensees are to consider both (i) normal activities and (ii) reasonably foreseeable activities that are consistent with activities and pursuits at the time the inadvertent intruder assessment is developed, the regulations do not specify a particular intrusion scenario to 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 inadvertent 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, and drilling for water, and other reasonably foreseeable pursuits that 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 4.2.1, to represent reasonably foreseeable inadvertent intruder activities. To limit speculation about future human activities, licensees are also permitted to use site-specific scenarios based on other reasonably foreseeable pursuits that are consistent with the activities and pursuits occurring in and around the site at the time of development of the inadvertent intruder assessment. Guidance on developing site-specific scenarios is discussed in Section 4.2.2. 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 in the inadvertent intruder assessment can be generic or site-specific. Regardless of the 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), or they may develop site-specific receptor scenarios. 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.

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

Types of Scenarios		Evaluation Purpose	Description
Plausible	Generic	All can be used to demonstrate compliance with the inadvertent intruder performance objective. Licensees should use the plausible scenario from which the inadvertent intruder would reasonably be expected to receive the greatest exposure to radiation from the waste to demonstrate compliance.	The scenarios used to inform the waste classification criteria at 10 CFR 61.55 that are consistent with normal activities including agriculture, dwelling construction, drilling for water.
	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 the assessment is developed.
	Reasonably Foreseeable		Reasonably foreseeable scenarios are based on: (i) normal activities; and (ii) other pursuits that are consistent with activities in and around the disposal site at the time the assessment is developed. Normal activities include agriculture, dwelling construction, resource exploration or drilling for water. The NRC staff continues to believe the generic receptor scenarios associated with normal activities are 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 the assessment is developed.
	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.

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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 4.2.1 in an inadvertent 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. 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 assumptions used in developing the receptor scenario (e.g., justify the inclusion (or exclusion) of a particular exposure pathway).

4.2.1 Generic Intruder Receptor Scenarios

The NRC used a limited number of generic scenarios based on normal activities to inform the development of 10 CFR Part 61 waste classification criteria (NRC, 1981a, 1982b, 1986a). Appendix G provides a summary of the assumptions and approaches used to develop the waste classification limits in 10 CFR 61.55. 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 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 for a reference disposal facility; these receptor scenarios helped establish waste classification criteria to be applied at all licensed disposal sites. The regulatory basis for the original 10 CFR Part 61 assumed that inadvertent intrusion occurred following a cessation of an active institutional control period administered by the land owner or custodial agent. Institutional control of the disposal site was expected to occur beyond the active institutional control period; however, control becomes increasingly difficult to ensure at longer times, and thus, was not relied upon to ensure safety. While the institutional controls are expected to be durable, 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 (see Section 9.0).

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) intruder-drilling, in which the intruder receives an acute exposure while drilling through the waste to install a water well

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

(5) intruder-well, 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.

4.2.1.1 *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.

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.

4.2.1.2 *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 the intruder installs a well to secure an adequate water supply for living needs (e.g., for a dwelling or agriculture). If groundwater quality or quantity is inadequate at a particular disposal site, this scenario may not be possible (see Section 4.2.2.1.2 for details on screening scenarios based on site-specific groundwater quality or quantity).

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).

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During drilling activities, the drilling crew is assumed to inadvertently drill through the waste, bringing some waste to the land 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 new borehole[1]. 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. This 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.

4.2.1.3 *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 hydrogeological 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 inadvertent intruder assessment to demonstrate compliance with

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[1] The term borehole is used to refer to the wellbore drilled to install a well. It is not to be confused with borehole disposal technology that may be used for disposal of certain types of radioactive waste.

10 CFR 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.

4.2.1.4 *Criteria for Selecting Generic Receptor Scenarios*

Licensees may adopt the generic receptor scenarios described in Section 4.2.1 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 4.2.2 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 4.1 through 4.4 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) and modify the generic receptor scenarios.

Reviewers should assess a licensee's analysis of whether the generic receptor scenarios are suitable given 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 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 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 4.1

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 assume residential construction. Residential construction 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 4.2.2 for guidance on screening scenarios based on site-specific information.

Example 4.2

A disposal facility is located in a geographic region that currently lacks of an adequate groundwater 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-drilling and -well receptor scenarios.

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 both groundwater dependent exposure pathways and drilling as an activity. Drilling may still need to be considered for other activities (e.g., petroleum extraction) if those activities are occurring in the vicinity of the site. The licensee should also demonstrate the expected persistence of the conditions used as a basis for excluding intruder activities and exposure pathways during the operational lifetime of the facility. For a more robust assessment, licensees could also evaluate the impacts of 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 groundwater recharge and lead to an adequate groundwater source at some time in the future. Section 4.2.2 provides guidance on using site-specific information to screen exposure pathways.

Example 4.3

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 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 4.2.24.2.2.2 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.

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. 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 scientific 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 4.2.2. 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.

Example 4.4

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.

Section 4.4.2 discusses guidance for evaluating the longevity of intruder barrier capabilities. Section 2.2.4 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).

4.2.2 Site-Specific Intruder Receptor Scenarios

Site-specific receptor scenarios, which are developed by the licensee, give licensees greater flexibility in developing the scenario(s) and enhance confidence that the inadvertent intruder assessment accounts for site-specific factors to demonstrate that the inadvertent intruder

performance objective is met while also allowing licensees to more efficiently use disposal capacity. 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 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 limit consideration of intruder activities that are site-specific to those that are consistent with activities occurring in and around the site at the time the inadvertent intruder assessment is developed to form reasonably foreseeable receptor scenarios. However, prudent licensees who are early in a land disposal facility's lifecycle may wish to consider reasonably foreseeable activities that may occur up to the closure of the land disposal facility to ensure that future revisions to the inadvertent intruder assessment would not result in significant changes to the receptor scenarios as land uses change over the lifetime of the land disposal facility.

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 reasonably 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 require a technical basis that considers 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 development of the inadvertent intruder assessment and extending to facility closure). The reviewer should evaluate the justification 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.

4.2.2.1 *Site-Specific Physical Information*

Physical information about the site includes information related to waste characteristics and disposal practices as well as site physical characteristics (e.g., the presence of natural resources such as water and its quality and quantity, soil conditions, topography, and climate). 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 drilling a well for water extraction and use) or other reasonably foreseeable pursuits that are consistent with activities in and around the site at the time of development of the inadvertent intruder assessment in which the person might be unknowingly exposed to radiation from the waste.

4.2.2.1.1 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 waste containing shorter-lived radionuclides (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 waste containing long-lived radionuclides, 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 consideration of land use information is discussed further in Section 4.2.2.2.

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 4.5). 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 4.4.

Example 4.5

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. The reviewer questions whether default scenarios need to be included.

Conclusion: While the alternate site-specific scenario may be appropriate given the cover depth, reviewers should confirm that the licensee's 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 4.2.2 for guidance on screening scenarios based on site-specific information.

4.2.2.1.2 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 4.6). Reviewers should evaluate the justification for modifying generic receptor scenarios or selecting site-specific receptor scenarios based on a site's physical characteristics.

Example 4.6

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. The reviewer questions whether this exclusion is appropriate.

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.

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 currently 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.

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.

4.2.2.2 *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 4.2.2.1 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 projecting land uses over the lifetime of the land disposal facility 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 the inadvertent intruder assessment is developed. However, prudent licensees who are early in a land disposal facility's lifecycle may wish to consider reasonably foreseeable activities that may occur up to the closure of the land disposal facility to ensure that future revisions to the inadvertent intruder assessment would not result in significant changes to the receptor scenarios as land uses change over the lifetime of the land disposal facility.

Reviewers should evaluate the justification provided for the selection of reasonably foreseeable scenarios. Reviewers may wish to involve State and local land use planning agencies in discussions if the licensee has not already requested their involvement.

4.3 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 inadvertent 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 modeling for the inadvertent 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 inadvertent 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 a 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 ensuring the abstraction is a reasonable representation of the disposal site and 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. Sections 2.2.3 and 2.7.4 of this document discuss general considerations for uncertainty and sensitivity analysis.

The numerical models used to implement the mathematical equations are 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. Section 2.2.1 of this document provides guidance on QA for technical analyses. Additional guidance can be found in Chapter 9 of NUREG-1199, NUREG-1200, and NUREG-1293 ((NRC, 1991a; 1994, 1991c). A justification for the conceptual model represented by each code 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.

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

4.3.1 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 4.4.

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 models of intruder barriers, 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

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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 4.7). 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 4.7

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 2.2.4 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 4.4.1 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 2.2.3 and 2.7.4 of this document discuss guidance on uncertainty.

4.3.2 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 as a result of the waste disposed at the site and inadvertent intruder activities onsite. 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.

4.3.2.1 *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 of 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. For instance, licensees may wish to represent a larger inventory in the intruder assessment than their waste acceptance criteria because the disposal facility provides sufficient margin for demonstrating compliance with 10 CFR 61.42, but the margin may be smaller for demonstrating compliance with 10 CFR 61.41. Regardless, the waste acceptance criteria, as described in Section 8.0, would need to be consistent with the results of all the technical analyses.

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 in the inadvertent 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 4.2.1 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 3.2). 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 assume no decay, if the assumption is conservative. 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, activities 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 *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 4.5), intruder activities envisioned in the receptor scenario, and the capabilities of intruder barriers to preclude intrusion. Section 4.3.1 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, in the intruder-construction scenario, it is typically assumed that the intruder 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

DRAFT

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.

4.3.2.3 *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 to members of the public are assessed in the performance assessment for demonstrating that the performance objective for protection of the general population is met. Receptor scenarios for the inadvertent intruder and member of the public are mutually exclusive and the performance assessment does not evaluate offsite exposures resulting from contamination that arises from inadvertent intruder activities. 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 inadvertent intruder 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 groundwater 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) in the inadvertent intruder assessment.

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 3.2 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.

4.3.3 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 3.3 of this document is generally applicable to an inadvertent 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, if applicable. 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 typically need to be considered in an inadvertent intruder assessment. Though onsite exposures are expected to bound offsite exposures resulting from inadvertent intruder activities, there may be some limited cases where offsite transport results in a larger exposure to the inadvertent intruder and should be evaluated in the inadvertent intruder assessment, if appropriate, to demonstrate compliance.

4.3.4 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 disposal units after the period of active institutional controls. As such, 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 in an inadvertent intruder assessment consists of converting radionuclide concentrations in environmental media to dose through various exposure pathways associated with an inadvertent intruder receptor scenario. Guidance on development of receptor scenarios is discussed in Section 2.5.4.3 of this document, and guidance on the dosimetry parameters is discussed in Section 3.4.2. Additional guidance applicable to modeling of exposure pathways in intruder assessment is 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 a combination of direct exposure, inhalation, and ingestion of contaminated water, soil, plants, and animal products, as appropriate for the receptor scenario.

Reviewers should evaluate the conceptual models that describe the human behaviors that lead to or control the amount of receptor exposure. Reviewers should confirm that conceptual models describing human behaviors controlling the amount of exposure are consistent with the receptor scenario and site conditions. 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 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 scenarios.

4.4 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 and demonstrate compliance with 10 CFR 61.42. 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 and other reasonably foreseeable pursuits that are consistent with activities in and around the site at the time the inadvertent intruder assessment is developed. 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 groundwater 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 capabilities of the barriers should be provided for the time period over which each barrier performs its intended function, including changes to the barrier during the compliance period that significantly affects its ability to protect the inadvertent intruder. These capabilities, including uncertainties, should be consistent with the performance attributed to the barriers in the inadvertent intruder assessment. Reviewers should use information gained from the inadvertent intruder assessment, independent calculations, and other appropriate quantitative analyses to confirm each barrier’s capabilities. Reviewers should 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.

DRAFT

The functionality and robustness of the barriers will be determined using the risk-informed graded approach described in Section 4.4.1 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 developing and providing a basis for intruder barriers.

4.4.1 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 inadvertent intruder assessment and resultant actions should ensure that high risks are not realized by an inadvertent intruder. 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 values 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, and performance periods).

Reviewers should 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 4.3.1 discusses guidance on modeling intruder barriers in the inadvertent intruder assessment. Section 4.4.2 discusses guidance on justifying the capabilities for intruder barriers modeled in the inadvertent intruder assessment.

4.4.2 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 2.2.4, 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.

During the operational, post-closure 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 inadvertent intruder assessment; and (2) the quality and completeness of the technical basis for the barrier capabilities.

4.4.3 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 inadvertent 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 an inadvertent breach because the barrier becomes indistinguishable from native materials and the potential degradation of the barrier over time

DRAFT

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. Though focused on decommissioning, the information is generally applicable to engineered barriers for land disposal facilities.
- 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 4.8). 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.

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. Even with reliance on vegetation, over long periods of time, a minimum erosion rate may 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) if it were plausible to consistently occur at a site.

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Example 4.8

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 an intruder 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.

4.5 Institutional Controls

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. Further, the institutional control period will be determined by the Commission. For the purposes of the inadvertent 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 unless otherwise authorized by the Commission, 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 in the inadvertent intruder assessment. 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.

If the Commission approves an institutional control period shorter than 100 years, then the inadvertent intruder assessment should assume inadvertent intrusion could occur following the Commission-approved institutional control period. If the Commission approves an institutional control period longer than 100 years, 10 CFR 61.59 still requires that licensees may not rely on institutional controls to preclude inadvertent intrusion in the inadvertent intruder assessment beyond 100 years following transfer of control of the disposal site to the owner. However, the Commission could approve an exemption under 10 CFR 61.6 to this requirement in 10 CFR 61.59.

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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 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 period and to eliminate, to the extent practicable, the need for ongoing active maintenance of the disposal site following closure. This section provides guidance on the process for developing site stability analyses, including technical information that a licensee should provide and that a reviewer should evaluate relating to the 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 10 CFR 61.41 and 10 CFR 61.42 performance objectives. Stability is defined in the regulation as "the capability of the disposal site (e.g., wasteform, disposal containers, and disposal units) to maintain its shape and properties to an extent that will not prohibit the demonstration that the land disposal facility will meet 10 CFR 61.41 and 10 CFR 61.42 performance objectives and will, to the extent practicable, eliminate the need for active maintenance after site closure." 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 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 (because processes external to the disposal site may impact site stability).

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 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 for a licensee 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 specific radionuclides. Consequently, it may be necessary for a licensee to impose limits (see Section 8.0) 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 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 period. 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).

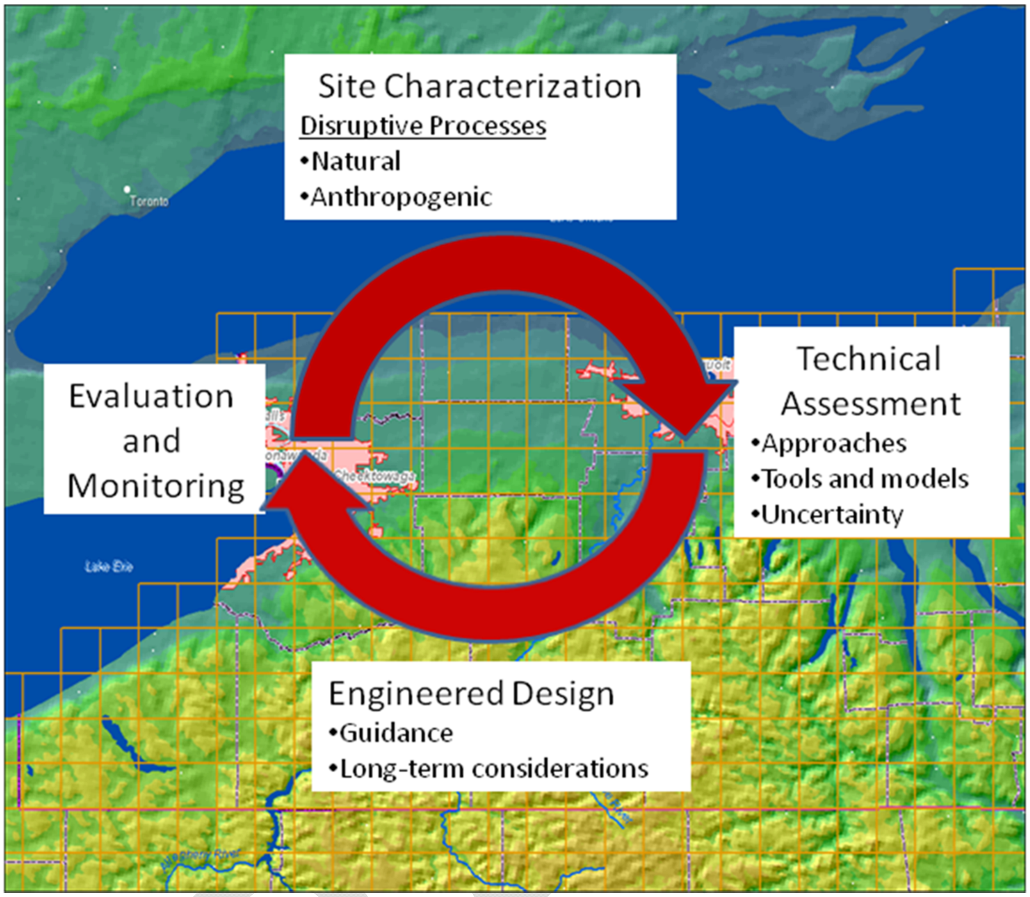

Figure 5-1 Main Elements of Site Stability Analysis

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 2.5.3) 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 site stability analysis.

The scope of the analyses needed for the site stability analysis 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 used more

frequently for long-term performance 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; 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:

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

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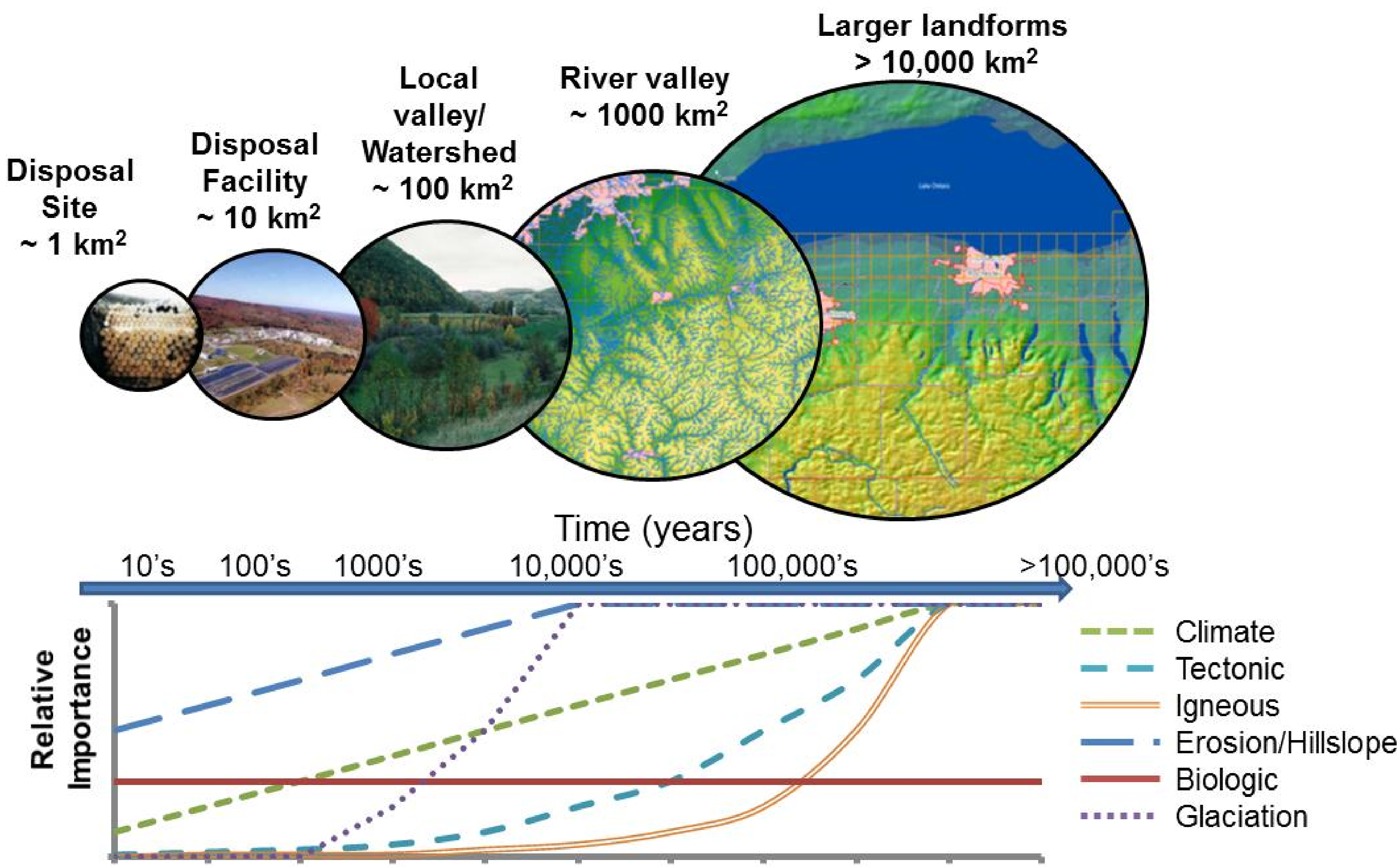

Figure 5-2 Spatial and Temporal Scales and NRC Staff Perspective on the Relative Importance of Various Geomorphological Processes Relevant to LLW Disposal.

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 compliance 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 inadvertent intruder assessment required by 10 CFR Part 61 (see Section 4.0) often mitigates the need to consider low frequency disruptive events by bounding the projected dose

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impacts that could result from disruptive events. Inadvertent 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. Site-specific inadvertent intruder scenarios that have limited to no direct disturbance of the waste or limited exposure times will commonly produce lower doses to intruders than the doses that may result to the public from disruptive processes or the generic receptor scenarios. The argument that disruptive processes and events do not need to be considered because an inadvertent intruder assessment was performed may be invalid when site-specific inadvertent intruder scenarios are used.

Licensees should use a screening process to determine which processes and events need to be considered in the site 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 LLW 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 and synergistic 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 are reduced through processes such 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 by a licensee 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 long-term stability 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 lithology 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, climatic processes and climate change, biological processes, and fires.

Climate and climate change have the potential to impact the stability of the disposal site. This section deals with climate change in terms of the natural cycling of climate, not human-induced climate change. Section 5.1.2 discusses anthropogenic impacts on climate. 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 is likely to 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 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 2.5.3, 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 of material eroded 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 WFTM 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 design (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 inadvertent 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. The direct impacts to the inadvertent 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 analyses timeframe for their waste disposal actions. Section 4.0 provides guidance for performing the inadvertent 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 detail in NUREG-1199 and NUREG-1200, and therefore, 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. Either 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. Iterative analysis may be necessary. 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. Technical basis should be provided for the performance of engineered barriers. 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.

DRAFT

Table 5-1 Summary of Applicability and Limitations of Erosion and Mass Wasting Codes for Long-Term Performance Assessment (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)

A licensee's site stability assessment should include the following 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 resulting from potential instability will not result in sufficient radiological risk (i.e., that 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 2.5.4.2, Section 2.5.4.3, and Section 4.2. 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 needed 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

DRAFT

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 (technical basis) 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. Technical basis for engineered barrier performance must be provided in either the design-based or model-based approach.

(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 ensured, 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 site stability

analysis 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 during the initial 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 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 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 2.2.4 (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 site stability requirements can be met. Staff expects the model-based approach may be iterative, and that the understanding of the significance of FEPs may evolve over time.

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 2.2.4 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 information 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 site stability analysis 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 2.2.3. 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

DRAFT

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 2.2.3, 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.

A licensee may undertake a variety of actions if site stability is not demonstrated. They 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. Or they may refine their modeling (if technically justifiable) and the refined model may demonstrate that FEPs that were previously believed to be significant actually have insignificant impacts.

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. Engineered surface covers can be significant barriers because they may contribute to a licensee demonstrating that one or more performance objectives will be met. Engineered covers may contribute to disposal facility performance by minimizing infiltration and slowing degradation of a 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 site stability analysis in waste disposal has been on erosion protection.

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 2.2.4, 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.

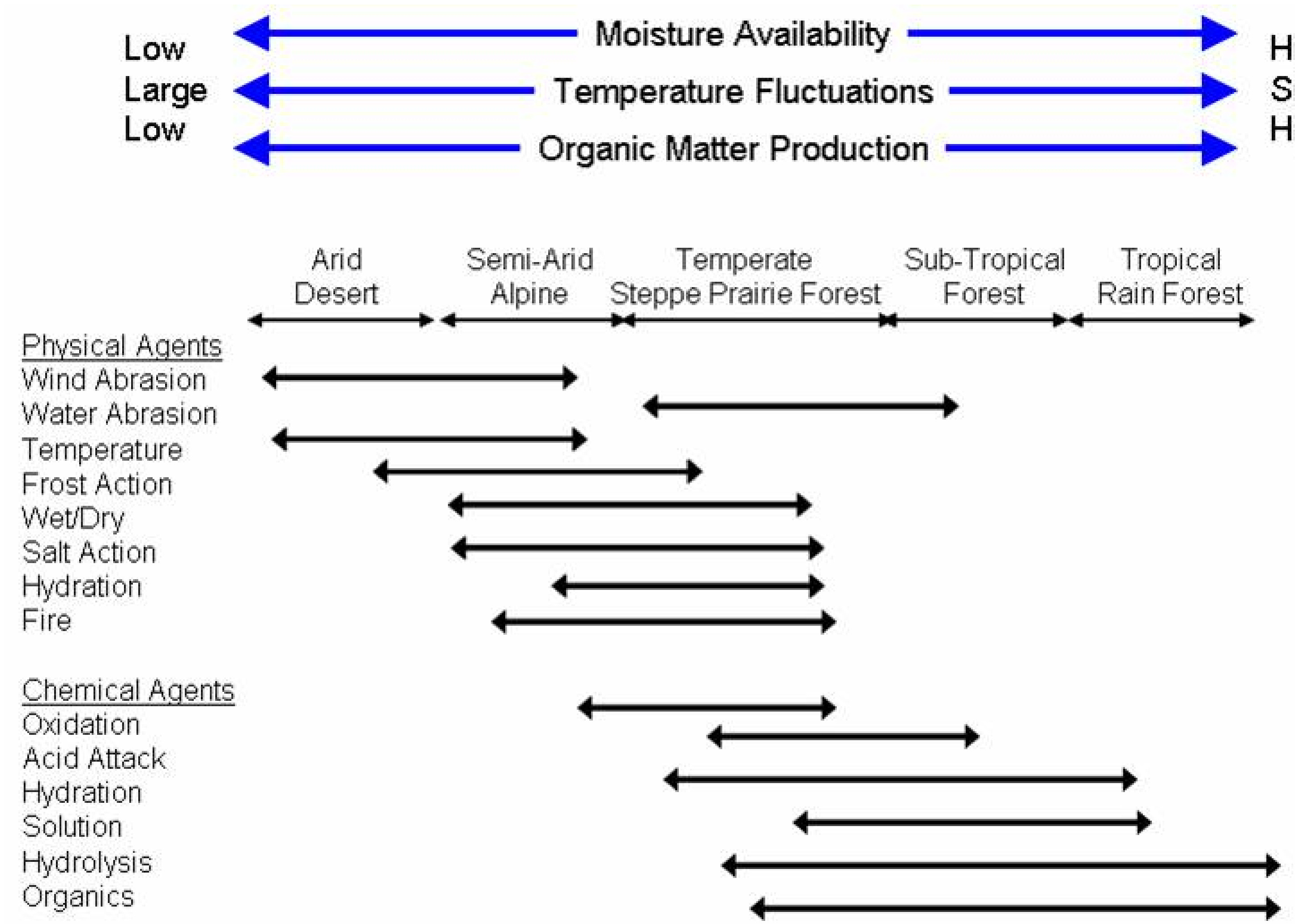

Figure 5-3 Macroscale Relationship between Climatic Variables, Environments, and Rock Weathering Agents: Occurrence of Weathering as a Function of Climate (NUREG/CR-2642)

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 will generally rely on conservative designs.

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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

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Licensees should use the following elements in their design of engineered barriers for long-lived waste:

- multiple, independent, and redundant[3] barriers,
- conservative approaches, and
- very high quality and durable materials.

5.3.2.1 *Conventional (Resistive) Covers*

Licensees can use conventional covers for different design functions. One common 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 over thickened 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

[3] Redundancy with respect to long-term engineered barriers is not meant to infer duplicative systems, such as multiple drainage layers in an engineered barrier. Redundancy is meant to refer to redundancy in the protective function that is desired, such as limiting the rate of erosion. For example, low relief design with proper slope configuration can limit erosion rates as well as use of a durable and appropriately sized riprap layer.

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 practicable, 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

- <u>Natural analogs</u>: 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 practicable. 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

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assumption coincides with the 10,000-year compliance period for a LLW facility with significant quantities of long-lived radionuclides.

- 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 compliance period for significant quantities of long-lived radionuclides. 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:

- attention to construction QA; QA is especially important to the successful short-term performance of the cover
- identification of the phenomena that have the greatest impact on total system performance
- 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).

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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 adequate performance data 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

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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.

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6.0 PERFORMANCE PERIOD ANALYSES

10 CFR 61.13(e) requires performance period analyses to:

(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 features of the design and site characteristics relied on to demonstrate compliance with the applicable performance objectives set forth in 10 CFR 61.41(b) and 10 CFR 61.42(b).

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 performance period is defined in the regulations to be the period of time following the compliance period. Performance period analyses are required only if the disposal facility is accepting significant quantities of long-lived radionuclides and the licensee has used a 10,000-year or longer compliance period. Table 6-1 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 compliance 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 6-2 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.

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. Table 6-2 shows how the performance period analyses may be risk-informed by licensees.

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[1] Long-lived radionuclide means radionuclides (1) where more than ten percent of the initial activity of the radionuclide remains after 1,000 years, (2) where the peak activity from progeny occurs after 1,000 years, or (3) where more than ten percent of the peak activity of a radionuclide (including progeny) within 1,000 years remains after 1,000 years. The first part of the definition represents radionuclides with approximately a 300-year or longer half-life. Examples of isotopes that are short-lived but produce long-lived progeny are provided in Table 6-1 (e.g., Am-241, Cm-242).

Table 6-1 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 should be considered as part of the LLW PA inventory, but not all isotopes may be included in the technical analyses. 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 6-2 Expected Level of Review Effort Associated With Performance Period Analyses

Radiation Hazard And Duration[1]	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[2]. 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[3]. 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] The terms *low*, *moderate*, and *high* in Table 6-2 refer to *relative* concentrations when waste was already determined to have significant quantities of long-lived radionuclides necessitating the performance period analyses

[2]Discussed in Section 6.2

[3]Discussed in Section 6.3.1.1.3

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 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 6.2) should be addressed in the analyses. Licensees should provide model support for analyses, as discussed in Section 2.2.4, 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.

6.1 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.

Table 6-3 describes the characteristics that will enhance isolation at most 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 6-3 apply to the design of disposal facilities while others apply to the site characteristics.

6.2 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 stability analyses (described in Section 5.0), including the FEPs analysis (Section 2.5). 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 guidance.

Table 6-3 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 groundwater plume requiring remediation (NYSDEC, 2008). Only a small amount of high-specific activity waste released into the environment can cause significant environmental impacts. 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 compliance period. However, 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.

6.2.1 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 and present the results of the uncertainty assessment. 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 the compliance period without modification provided that the calculations are complete with respect to including key FEPs relevant to the performance period. The compliance 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 analyses. The analyses that are developed for the compliance 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 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, 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 analyses. However, the representation of a particular FEP in the compliance 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.

Section 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 6.2.2). 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 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 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 FEP processes will reduce the FEPs applicable to the performance period but some of the FEPs eliminated in the compliance period may apply for the performance period.

6.2.2 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 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 B 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 at the disposal site 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.

6.2.3 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

DRAFT

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 2.5.4.2 and 2.5.4.3). As necessary, the behavior of potential receptors over the performance period should be modified using present-day climatic analog locations. For example, groundwater may not be potable in the present day, but the long-term analyses could examine whether that site characteristic is expected to be present (or absent) 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 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.

6.3 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 6-1 is a diagram of the recommended approach to the analyses for the performance period.

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.

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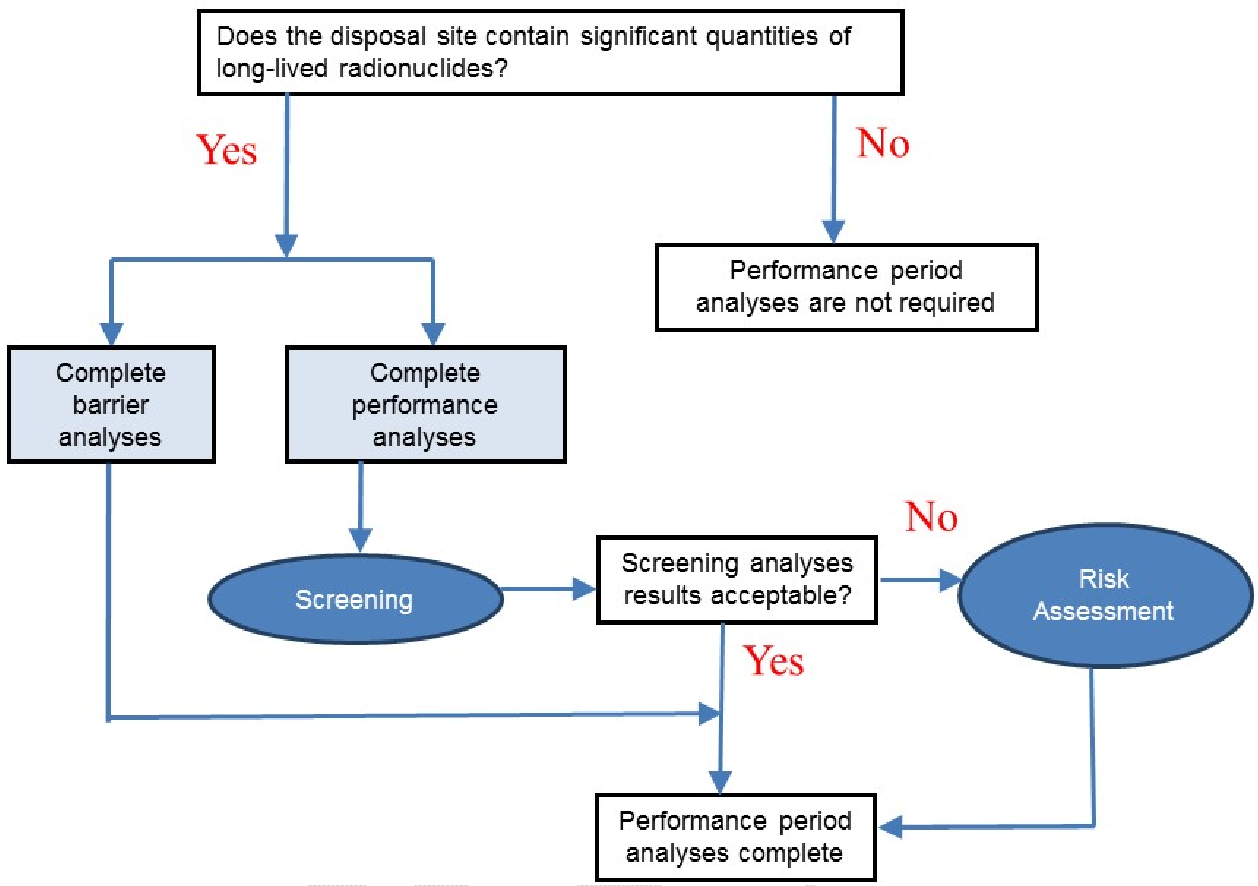

Figure 6-1 Recommended Approach to Conducting Performance Period Analysis

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.

6.3.1 Types of Analyses

The analyses for the performance period may be quantitative, semi-quantitative 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

6.3.1.1 *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 8.0) 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.

6.3.1.1.1 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 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

[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.

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 at the disposal site
- 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 addition, the dilution during transport arising from the geometry of the waste, hydrogeological system, and infiltration processes should be included in the screening assessment.

6.3.1.1.2 Quantitative Analyses

If screening analyses have been performed and the projected results are not acceptable (see Section 6.3.1.1.3), 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 10 CFR 61.41(b) and 10 CFR 61.42(b) 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 inadvertent intruder assessment completed for the compliance period. The guidance provided in Sections 2.0, 3.0, and 4.0 for the compliance 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 10 CFR 61.41(b) and 10 CFR 61.42(b) requirements will be met is to minimize releases to the extent reasonably achievable. There is no dose limit associated with the performance period analyses.

Uncertainties associated with the performance period may be larger than those associated with the compliance period. 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- or 10,000-year compliance period. However, the rate of carbonation could be sufficient enough to reduce the protective passivation of the rebar after the compliance period, leading to deterioration or failure of the cementitious barrier during the performance period.

Figure 6-2 is an example of the scope of the technical analyses for the compliance period and performance period for a hypothetical site. Figure 6-2 has shaded areas to show: that some processes and events will only be applicable to the compliance 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 compliance 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, 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 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.

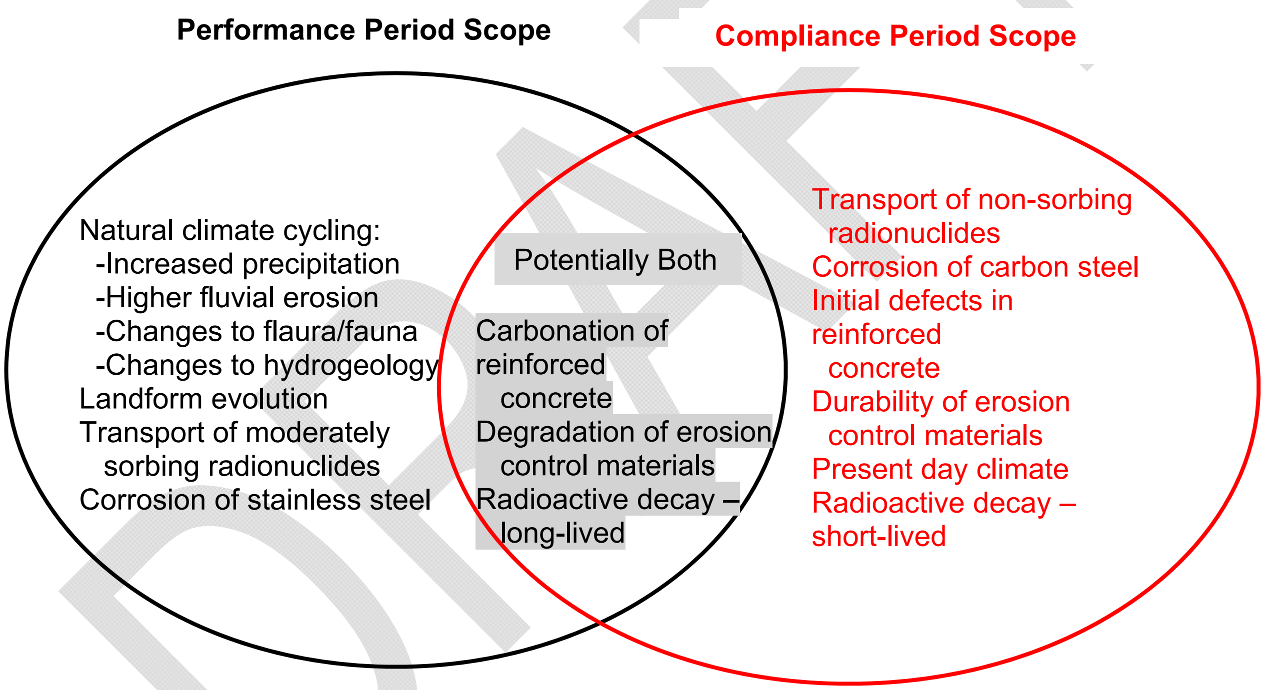

Figure 6-2 Scope of the Technical Analyses for the Compliance Period and Performance Period for a Hypothetical Site

6.3.1.1.3 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(b)) and to minimize exposures to any inadvertent intruder to the extent reasonably achievable (10 CFR 61.42(b)). 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.

Dose limits are not established for the performance period in 10 CFR 61.41(b) and 10 CFR 61.42(b). 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. 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 compliance period for significant quantities of long-lived radionuclides (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 10 CFR 61.41 public annual dose limit for the compliance period (25 mrem/yr), 10 CFR 61.42 intruder annual dose limit for the compliance period (500 mrem/yr), 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 6.1).

DRAFT

Example 6.1: A disposal site is located in a semi-arid environment in the Southern US 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 2-2 concentrations. The licensee determined that the site would dispose of significant quantities of long-lived radionuclides and therefore used a 10,000-year compliance period. 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 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 groundwater. 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.

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

6.3.1.2 *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 barriers (see Section 7.0). 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 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 analysis is sufficient for the performance period analyses.

6.3.1.2.1 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 examine 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 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 a one-off 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 consequence that the waste could produce. However, the usefulness of this type of analysis is reduced when the likelihood for the hypothetical consequences becomes overly unlikely. 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 6.2 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

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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 may perform, the analyses may not provide a correct representation of how the system is expected to perform.

6.3.1.2.2 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.

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Example 6.2 – 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)

7.0 DEFENSE-IN-DEPTH

Defense-in-Depth:
The use of multiple, independent, and, where possible, redundant layers of defense so that no single layer, no matter how robust, is exclusively relied upon.

The core of the NRC's safety philosophy has long included the concept of defense-in-depth. Under 10 CFR 61.2, defense-in-depth is defined as "the use of multiple, independent, and, where possible, 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 61.12(o) require that land disposal LLW facilities identify defense-in-depth protections, including a description of the capabilities relied upon to maintain safety, and provide a basis for the capability of each defense-in-depth protection.

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 protections help to provide reasonable assurance that 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 61.12(o) 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 their capabilities including 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 10 CFR Part 61.13 technical analyses (e.g., performance assessment, intruder assessment, site 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 identifying and describing defense-in-depth protections at a land disposal facility. Sections 7.1 and 7.2 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 7.3 provides guidance on identifying and describing defense-in-depth protections during the operational and post-closure phases of the land disposal facility lifecycle.

7.1 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 systems and 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 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.

The regulations in 10 CFR Part 61.12(o) require licensees to explicitly identify and 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.

7.2 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 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. The use of defense-in-depth protections is 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 <u>multiple</u>, <u>independent</u>, and, where possible, <u>redundant</u> 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.

7.2.1 Multiple Layers

Multiple layers of defense provide confidence that: (1) accidents can be prevented, (2) the effects of an accident can be lessened should a malfunction or accident occur, and (3) 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 7-1).

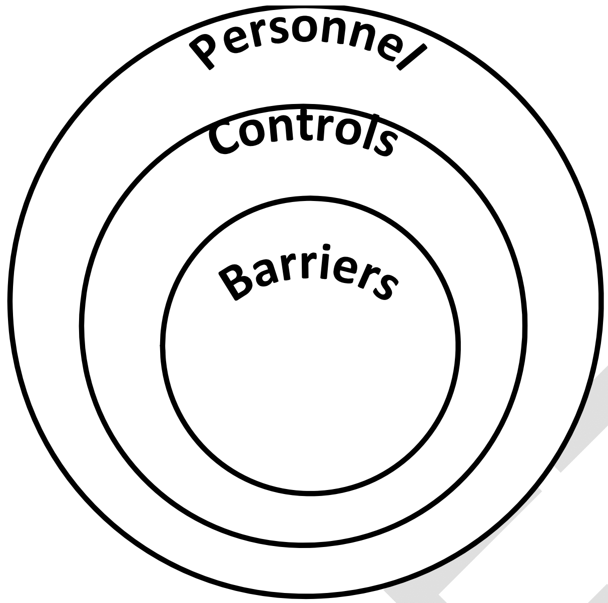

Figure 7-1 Multiple Layers of Defense

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 action 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 7-2 depicts approximate time periods over which safety functions for barriers, controls, and personnel may be appropriate.

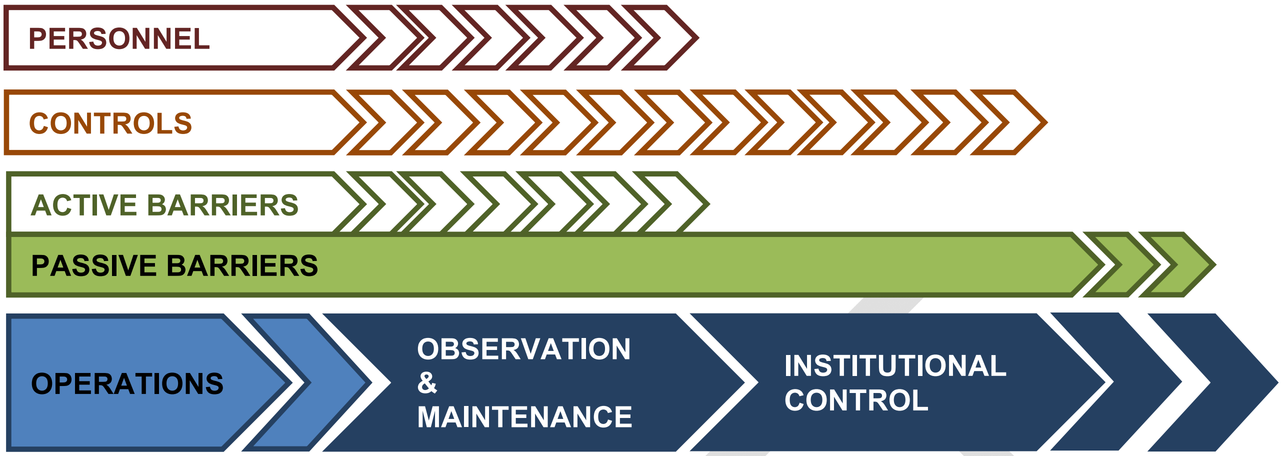

Figure 7-2 Land Disposal Facility Lifecycle and Timeframes for Defense-in-Depth Layers (Duration of lifecycle timeframes are not to scale. Dark blue timeframes are considered the post-closure period.)

7.2.1.1 *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 licensee's ability to demonstrate that the land disposal facility will meet 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 to: (1) prevent or limit the contact of water with the waste; (2) limit the release or rate of release of radioactivity from the waste; or (3) 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 to 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 and erosion of 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 conditions 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.

7.2.1.2 *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).

7.2.1.3 *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.

7.2.2 Independent Layers

In addition to <u>multiple</u> layers of protection, which are discussed in Section 7.2.1, 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. An independent layer should provide a safety function that is not dependent upon other layers of defense in order 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 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. 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.

7.2.3 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 redundant layers of protection, where possible. The use of redundant layers increases confidence that safety is not reliant upon any single layer. Redundancy is the duplication of capabilities 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, where possible, 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, where possible, 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 of the safety function 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.

7.2.4 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 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 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 7.3.3.2 for each post-closure period. Section 2.5.4 discusses the terms used to describe scenarios to be included in 10 CFR 61.13 technical analyses (i.e., reasonably foreseeable, less likely, but plausible, and implausible). These terms and types of scenarios can also be used to describe the capabilities of defense-in-depth protections and their supporting bases.

7.2.5 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 waste containing significant concentrations of long-lived radionuclides, additional layers of protection may be needed to account for the uncertainty associated with projecting performance over very long time periods. For shorter-lived hazards, fewer layers of protection may be sufficient.

7.3 Defense-in-Depth Protections

The regulations at 10 CFR 61.12(o) require licensees to identify and describe the defense-in-depth protections for the land disposal facility. The licensee must identify defense-in-depth protections, describe the capabilities of each protection relied upon to maintain safety, and provide a basis for the capabilities of each defense-in-depth protection. Licensees should identify the defense-in-depth protections and describe their capabilities 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. This section describes acceptable approaches licensees may take to identify defense-in-depth protections, describe the capabilities of each defense-in-depth protection relied upon for safety, and justify the capabilities of each defense-in-depth protection.

At a minimum, licensees should identify the defense-in-depth protections, describe the capabilities, or safety functions, that the protections perform, and provide a technical basis for the safety function provided by each protection. Because the NRC's use of the defense-in-depth philosophy is intended to deliver a design that can handle uncertainties in knowledge of facility behavior, component reliability, or operator performance that might compromise safety, licensees should also describe, either qualitatively or quantitatively, the margin available to

maintain safety. As described in Section 2.3 of this guidance, licensees should identify the regulatory requirement to identify 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 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 10 CFR 61.13 analyses to identify and describe defense-in-depth protections at the land disposal facility and the safety margins that the protections provide.

In some cases, licensees may need to consider whether additional features, events, and processes or alternative scenarios than those considered for compliance with the performance objectives might be appropriate to consider solely for identifying that defense-in-depth protections are included (see Section 2.5) or for describing the margins available to maintain safety. 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 of compliance with the performance objectives. However, for the purpose of identifying that defense-in-depth protections are provided and describing the safety margin the protections provide, 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.

7.3.1 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 7.2.1 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 and when it is not possible to provide a redundant layer for significant defense-in-depth protections.

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, controls, and personnel 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)
- natural characteristics (e.g., hydrogeology) of the disposal site that are intended to contain and isolate the waste
- controls such as institutional controls, which are designed to limit access to the disposal site for a limited period of time

- 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 10 CFR 61.13 technical analyses. In some cases, the layers identified to describe defense-in-depth may not be represented in 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 10 CFR 61.13 technical analyses. 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, where possible, redundant layers of defense, so that no single layer is exclusively relied upon for safety.

As part of the identification of defense-in-depth protections, 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. Licensees should identify the layers for which a redundant capability or safety function is not possible or necessary and should provide a basis demonstrating that a redundancy is not possible. Acceptable approaches for demonstrating that redundancy is not possible are discussed in the next section.

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 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. If a redundant layer is not identified, reviewers should confirm that the licensee has provided an adequate basis to support that a redundant layer is not possible for significant defense-in-depth protections. Additional detail on an adequate basis to demonstrate that a redundant layer is not possible is included in the next section. Reviewers should also confirm that the licensee has identified which layers ensure independence. Independence should be ensured 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.

7.3.2 Description of Capabilities (Safety Functions)

Licensees should describe the capabilities, or safety function(s), provided by each layer that is identified as a defense-in-depth protection for 10 CFR 61.12(o). 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 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 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 10 CFR 61.13 analyses is provided in their respective sections of this document (Sections 3.0 through 6.0).

For a land disposal facility, the safety functions often are focused 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 to the general environment. In addition, safety functions cover other considerations such as maintaining structural stability or limiting exposures to radioactivity. The safety function(s) of a layer of defense may vary depending on the performance objective. In addition, a layer of defense may provide more than one safety function. Licensees should clearly identify the capabilities the layer provides 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. The capabilities of the redundant layer need only be comparable, not identical, to the capabilities provided by the primary layer of defense. For example, a waste container may be identified as a primary layer of defense during the post-closure period to limit the release of radionuclides from certain waste streams. A second waste container, while providing an identical redundancy to limit the release of radionuclides, would typically be neither practical nor necessary. Rather, other layers of defense, such as natural site characteristics, that also limit or slow the release of radionuclides from the disposal site, could provide redundancy for the waste container because the other layers offer comparable safety functions in terms of radionuclide release to the waste container.

If a licensee determines that redundancy for a significant defense-in-depth protection is not possible, the licensee should provide a basis supporting the determination. In deciding whether a redundant layer is possible, licensees may consider physical, technological, or economic limitations. However, the additional cost of limiting inventory is typically not expected to be overly burdensome from either a physical, 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 redundant layers of defense may not be possible for technological or economic reasons. Regardless of the basis for demonstrating that redundancy is not possible for a primary defense-in-depth protection, the licensee should provide justification that reasonably foreseeable and plausible scenarios would not result in significant consequences should they occur when it is not possible to provide redundancy for a significant defense-in-depth protection. Licensees can draw risk insights from the results of the 10 CR 61.13 analyses to support a justification that significant consequences would not result for reasonably foreseeable and plausible scenarios.

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 10 CFR 61.13 analyses. For instance, if a waste container is identified as a layer of defense used to provide 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 contact with the 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 the10 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 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 should 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 or 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.

Licensees should also describe the uncertainty in each layer's ability to perform its intended safety function. 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 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 capability, or safety function, of each layer to ensure that it clearly describes how the layer provides defense-in-depth protections and which

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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, though not necessarily an identical, capability to the primary layer's safety function. If a licensee is not able to identify another barrier that could provide a comparable safety function for redundancy, reviewers should confirm that a comparable safety function is not possible and that the lack of redundancy would not result in significant consequences for reasonably foreseeable and plausible scenarios.

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 that 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 10 CFR 61.13 analyses to ensure that the layers and their safety functions have been represented in the 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, where possible, 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. Reviewers should coordinate their review of the description of uncertainty with the reviews of 10 CFR 61.13 analyses to ensure that the uncertainty descriptions are generally consistent, and that the licensee described 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.

7.3.3 Basis for Capabilities

After describing the safety function provided by each layer identified as a defense-in-depth protection, licensees should describe how the layers will maintain safety and how 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. For layers of defense that provide one

or more significant safety functions, licensees should provide a 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 be achieved 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. 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 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 develop the basis for the performance of layers 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 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), inadvertent 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.

Licensees may use the results of analyses, such as barrier analyses including one-off or what-if types of analyses, to demonstrate that adequate independence and, where possible, redundancy is provided and that no single layer is relied upon for safety. The results of these analyses can be used to demonstrate that if any single barrier fails to perform, another barrier is available to provide a similar and adequate level of protection. The results of 10 CFR 61.13 analyses can also be used to demonstrate that a lack of redundancy combined with common-cause failures would not result from reasonably foreseeable or less likely, but plausible scenarios. If a lack of redundancy or common-cause failure were to occur for plausible scenarios, the licensee should demonstrate that the consequences would not be so large as to require intervention today. Consequences that may require intervention today are discussed in the following sections for each time period with consideration of 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 licensee is constructing the facility, receiving waste for disposal, or preparing the facility 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 includes the compliance period. For facilities disposing of waste containing significant quantities of long-lived radionuclides, 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 identification and description of defense-in-depth protections may be markedly different for each phase.

The following sections describe considerations for licensees and reviewers for the two major lifecycle phases of a land disposal facility and provide guidance on describing a land disposal facility's safety margin provided by the defense-in-depth protections.

7.3.3.1 *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 support the identification and description of the defense-in-depth protections that are included. The defense-in-depth protections identified and described for an operating land disposal facility are expected to be similar to those 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 10 CFR 61.13 analyses conducted for the operational period 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 their uncertainty ensure safety during operations by limiting the likelihood or consequences associated with 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, where possible, and a stronger basis for independence among the layers may be necessary. For the purposes of defense-in-depth, reviewers should consider potential exposures during operations of a land disposal facility as significant 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, and

where possible, improved independence or reduced uncertainty in the safety function of the layers.

7.3.3.2 *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 and natural characteristics of the disposal site that are intended to contain and isolate the waste. In addition, defense-in-depth protections may include controls such as institutional controls and waste acceptance requirements.

As a result of uncertainty in the behavior of the layers of defense during the post-closure period, 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 additional inventory controls to limit the amount of waste disposed at the disposal site. Development of waste acceptance criteria is described further in Section 8.0. Diversity in the capabilities of the passive safety protections provided by the disposal site (e.g., waste form, container, engineered features, depth of disposal unit below the land surface, hydrologic and geochemical characteristics of the disposal site) increases the resilience of the disposal site to unanticipated failures or external challenges and compensates, in part, for uncertainties in the long-term estimation of performance of the disposal site.

For the post-closure period, licensees can draw upon risk insights gained from their results of 10 CFR 61.13 post-closure analyses (i.e., performance assessment, intruder assessment, and stability analyses) rather than developing specific analyses to identify that defense-in-depth protections are included and then describe their capabilities. 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. The post-closure period is subdivided into up to two timeframes: the compliance period and, if required, the performance period. Depending upon the waste received, the performance period may not apply to the land disposal facility and defense-in-depth protections 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 two 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 sensitivity analyses to support the identification of the defense-in-depth protections. For instance, Section 6.3.1.2 describes how to conduct barrier analyses for demonstrating compliance during the performance period. Barrier analyses are commonly performed as part of a performance assessment, and though the guidance in Section 6.3.1.2 is focused on the performance period, it is generally applicable to conducting barrier analyses for the compliance period as well. 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 when additional layers of defense may be needed.

To support the description of the capabilities of the layers of defense, licensees should examine not only the reasonably foreseeable scenarios considered for demonstrating that the performance objectives will 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 or their characteristics (e.g. redundancy, independence) may be needed to demonstrate that adequate defense-in-depth protections are included for each of the post-closure time periods.

7.3.3.2.1 Compliance Period

In terms of the disposal site and design, licensees should demonstrate that the margin of safety provided 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 an adequate margin of safety, licensees could show that probabilistic dose curves derived from 10 CFR 61.13 analyses are below designated limits. 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, where possible, 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. Licensees should demonstrate that the 95th percentile of annual doses from probabilistic analyses of the central scenario 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 for 10 CFR 61.13 analyses 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, where possible, 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, where possible, 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 10 CFR 61.13 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, where possible, redundancy will be provided to ensure that common-cause failures are minimized and adequate redundancy in the safety function are provided so that a significant exposure is highly unlikely to occur.

7.3.3.2.2 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 during the compliance period. 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 through the results of the 10 CFR 61.13(e) analysis that 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 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 performance period such that significant consequences are minimized for plausible scenarios. Demonstrating that releases and exposures are minimized to the extent reasonably achievable will entail defense-in-depth protections. In some cases, the level of minimization reasonably achievable may still result in potential significant consequences at a particular site. Once licensees demonstrate that the releases and exposures will be minimized to the extent reasonably achievable, licensees should demonstrate that an adequate margin of safety is provided by the layers of defense for the performance period such that significant consequences, which would almost always justify intervention should they occur, are minimized for plausible scenarios. To demonstrate that an adequate margin of safety is maintained during the performance period, licensees should demonstrate using the results of the 10 CFR 61.13(e) analysis 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 performance period are considered higher-risk disposal facilities. Licensees should employ additional layers of protection or ensure that sufficient independence and, where possible, 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.

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8.0 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 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 8-1 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.

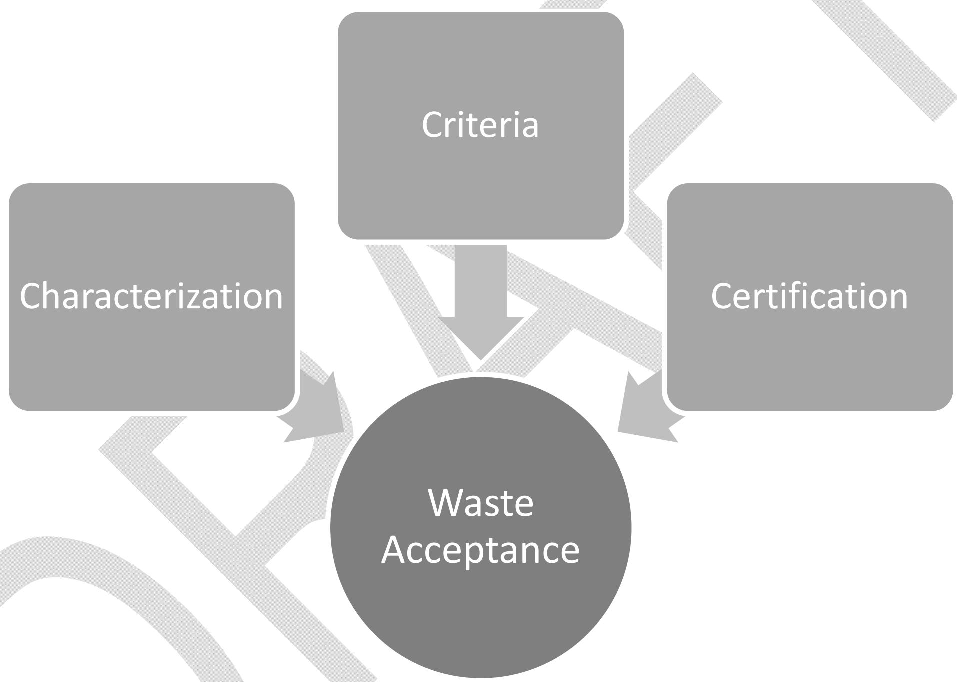

Figure 8-1 Waste Acceptance Components

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 8.1 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 8.2 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

8.3 describes information that licensees should include in a certification program to ensure that waste received at the disposal facility is acceptable for disposal.

8.1 Waste Acceptance Criteria

Section 61.52 of 10 CFR Part 61 requires that all waste disposed 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, under 10 CFR 61.58(g), 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.

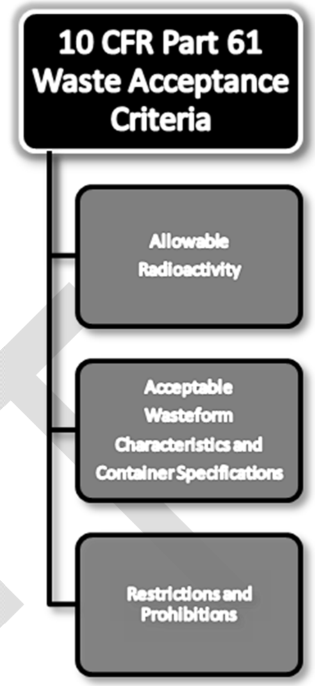

Figure 8-2 Components of 10 CFR Part 61 Waste Acceptance Criteria

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). The regulations require that the waste acceptance criteria specify allowable activities and concentrations of specific radionuclides, acceptable wasteform characteristics and container specifications, and restrictions or prohibitions on waste, materials, or containers. Figure 8-2 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.

8.1.1 Allowable Activities and Concentrations

The waste acceptance requirements of 10 CFR Part 61 afford licensees the option to develop allowable limits for radioactivity from the technical analyses required in 10 CFR 61.13, the waste classification limits in 10 CFR 61.55, or a combination of results from the technical analyses and the waste classification limits. For instance, licensees disposing of waste that is similar to the waste streams considered in the development of the waste classification limits (i.e., Table 1 and Table 2 of 10 CFR 61.55) may wish to rely on those limits. Whereas, licensees disposing of waste streams beyond those considered for the waste classification requirements may wish to develop limits from the results of their technical analyses. Licensees with facility designs, operational practices, or site characteristics that differ significantly from those considered to

develop the waste classification limits should develop site-specific waste acceptance criteria. The characteristics of the waste, the disposal site, and the design are the primary determinants of risk from near-surface disposal of radioactive waste. Not all radioactive waste streams may be suitable for near-surface disposal. Regardless of the method selected to develop allowable activities and concentrations, licensees must demonstrate that the Subpart C performance objectives will be met using technical analyses (i.e., 10 CFR 61.13).

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 Section 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.

8.1.1.1 *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. Figure 8-3 depicts a general process for developing allowable limits from the results of the analyses. 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 that are translated to per package or per shipment limits. Proposed limits for specific waste streams may be more appropriate when unique factors may affect meeting one or more of 10 CFR Part 61 performance objectives. These factors may include, but are not limited to, 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 select 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.

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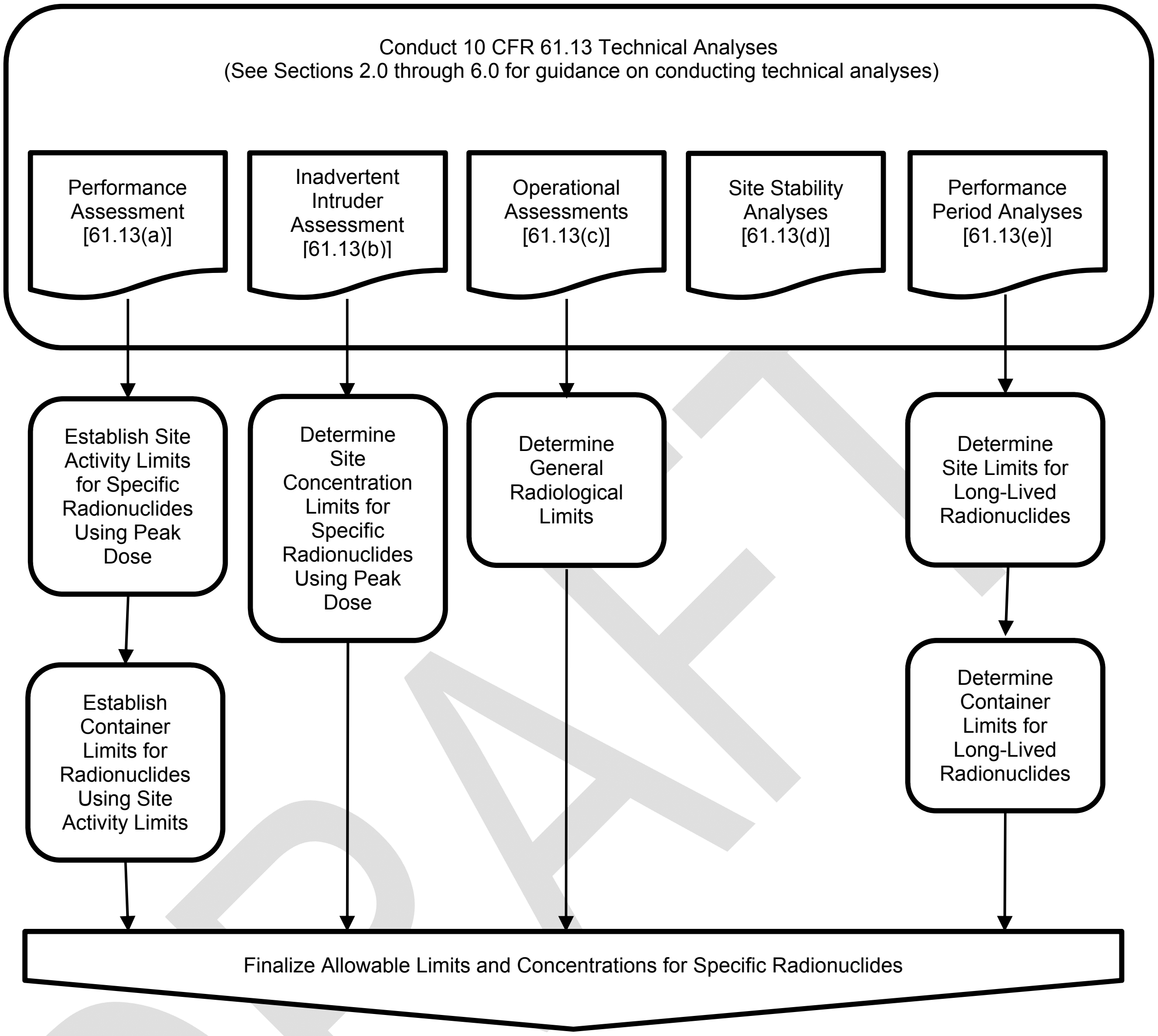

Figure 8-3 Example Process for Developing Allowable Limits Derived from Technical Analyses

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:

$$Limit_{i,s} = \frac{Dose\ Limit_s \times Activity(0)_i}{Peak\ Dose_{i,s}} \qquad (8.1)$$

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*.

For radionuclides that have disposal site activity and concentration limits, licensees would need to determine limits for individual containers so that a waste shipment to the disposal facility can be certified that the allowable limits are met and the waste is acceptable. In developing limits for individual containers, licensees should ensure that the assumptions and methods used are consistent with the conceptual models in the corresponding technical analyses. For example, licensees may be able to develop higher container concentration limits than the average site concentration limit determined by the inadvertent intruder assessment because of mixing with non-contaminated materials such as backfill. However, licensees should demonstrate that facility design, procedures, and controls would provide confidence that exceeding the average site concentration over a volume equivalent to the volume evaluated in the intruder assessment would not be likely.

Once licensees have developed radionuclide specific limits based on the results of the various technical analyses, licensees should finalize the allowable limits by selecting the limit that is most protective. For example, if a container limit is developed that demonstrates that the general population will be protected, but a container limit developed to demonstrate protection of the intruder is more protective, licensees should select the lower value.

Licensees should clearly identify the technical basis for each allowable limit specified in the waste acceptance criteria. The basis for each limit is typically derived from the results of the technical analyses. However there may be other bases for the limits such as other regulatory requirements (e.g., limits on fissile materials). The basis for each proposed limit should identify the performance objective(s) or other regulatory requirements, if applicable, that the limits are designed to demonstrate. 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 describe why each proposed limit is sufficient to demonstrate that the performance objectives, or other regulatory requirements, if applicable, 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 also describe in the technical basis supporting the allowable limits how variability and uncertainty in anticipated inventories are accounted for 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 the environment, the conservatism in the analyses, and the amount of information available to support the assessment. Figure 8-4 shows the relative confidence that allowable limits derived from technical analyses will be protective as a function of these variables.

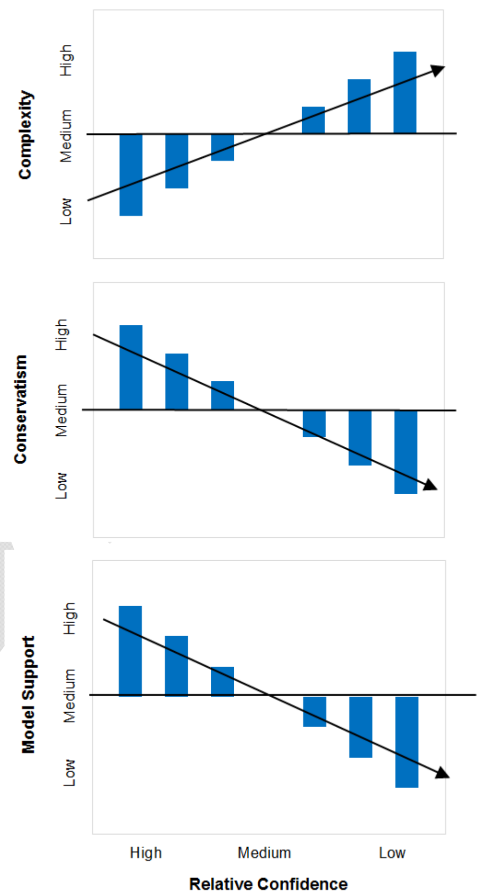

Figure 8-4 Influence of Key Variables on the Relative Confidence

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 derived operational limits because they will have high confidence. 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. The uncertainty in the calculated risk will be an influence of the derived operational 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.

Reviewers should coordinate reviews of the adequacy of the allowable limits with the reviews of the technical analyses required to meet 10 CFR 61.13 (see Sections 2.0 through 6.0). 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 a non-linear function of the source term concentrations.

Reviewers should 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). The spatial extent or distribution of radionuclide inventory in the disposal site may 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.

Although allowable limits will not typically be derived from the site stability analyses, 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 8.1.2 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 8.1.2).

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 ingrowth 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.

8.1.1.2 *Allowable Limits Derived from Waste Classification*

Licensees who elect to develop allowable limits for radionuclides from 10 CFR Part 61 waste classification requirements may simply report the concentration limits reported in 10 CFR 61.55 and demonstrate that the results of 10 CFR 61.13 technical analyses meet the respective performance objectives. 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 used to determine which waste characteristics requirements in 10 CFR 61.56 are necessary. Classification is also 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 in a manner that limits potential exposures, including

those to an inadvertent intruder, based on the hazard and stability of the waste. Figure 8-5 illustrates the waste classification and segregation requirements for LLW. Licensees relying on the waste classification system to develop allowable limits must 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 8.1.2 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 (i.e., Table 1 and Table 2). 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).

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. See Appendix G for a summary of the approaches and assumptions used to develop the waste classification limits in 10 CFR 61.55.

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.

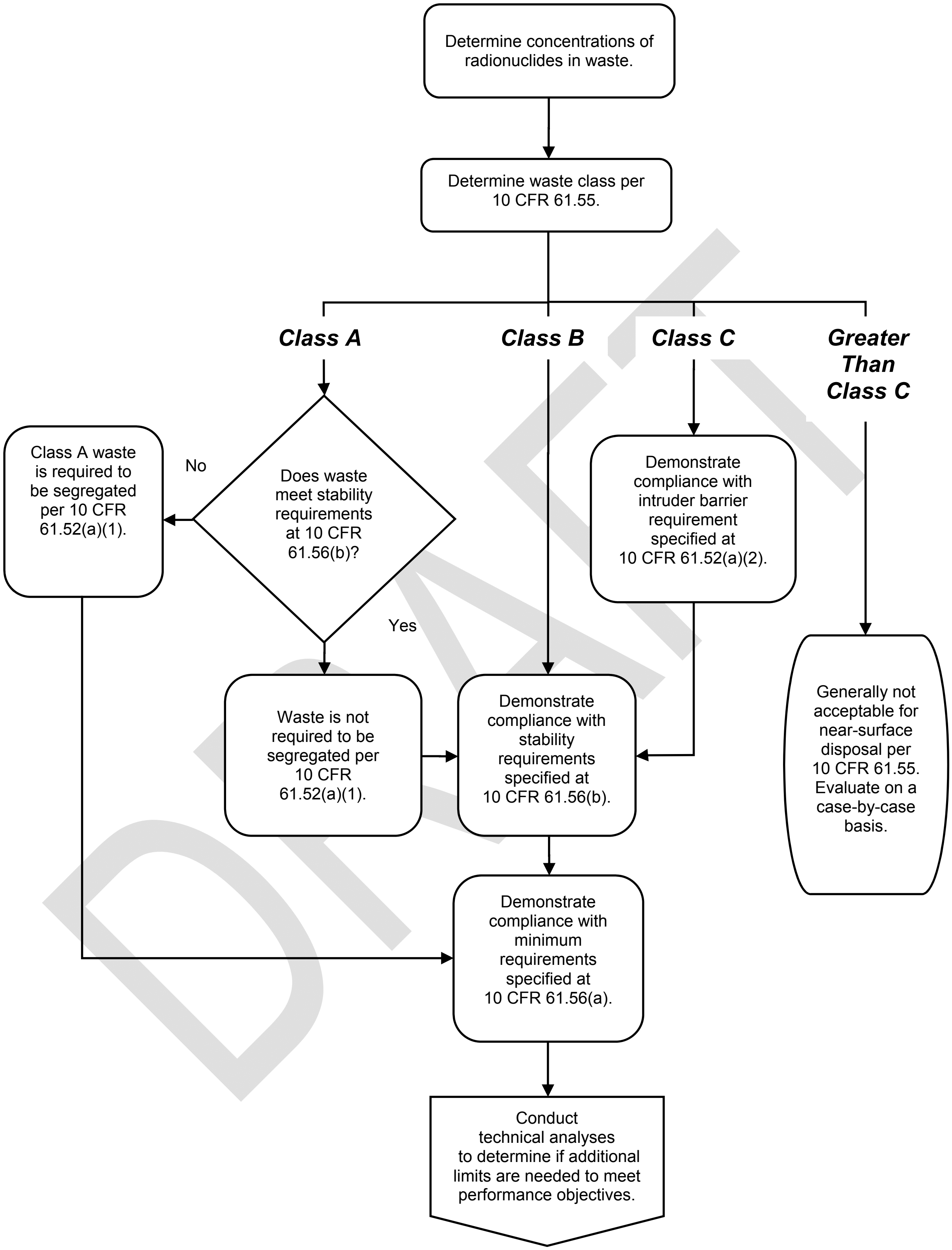

Figure 8-5 Waste Classification and Segregation for Waste Classes

Wastes that need to be placed in a stable form and disposed 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 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 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 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. 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 limitations or restrictions, 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 8.1.1.1 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," (BTP WCWF) 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 , "Concentration Averaging and Encapsulation Branch Technical Position, Revision 1," (BTP CA) (NRC, 2015a). Guidance is also available in Section 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.

8.1.1.3 *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. 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.

8.1.1.4 *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:

$$\sum_{i=1}^{N} \frac{Activity_i}{Limit_i} \leq 1 \qquad (8.2)$$

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 8.1.2).
- Limit or prohibit further disposal of a certain type of waste (see Section 8.1.3).

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 necessary. 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 as defense-in-depth protections, the licensee should provide a basis that defense-in-depth protections remain adequate in light of the proposed change.

8.1.2 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. 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
- 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 provide 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. 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 should also identify which performance objective(s) the criteria support and whether the criteria provide defense-in-depth protections. 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. The criteria should provide reasonable assurance that the longevity required of the wasteform and container capabilities can be adequately demonstrated. The basis for the criteria may include traditional engineering tests or specifications for waste containers. In other cases, the criteria may be supported by the results of laboratory testing, predictive modeling, or comparison to analogs.

NRC has developed guidance in the form of a BTP (NRC, 1991b) for waste generators on wasteform test methods (BTP WFTM), "Technical Position on Waste Form, Rev. 1" and results that are considered acceptable for complying with 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 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 WFTM (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, 4.0, and 5.0). 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 and the identified 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 8.1.1.1).

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 inadvertent 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.

8.1.3 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.

8.2 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 is 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 radionuclides, which have specified allowable activities or concentrations for acceptance, per unit volume or mass, radiation dose levels at the surface of the container, and external contamination levels on the surface of the container as well as associated uncertainty.

- **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 that 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 and its associated uncertainty. This information should be identified from waste acceptance criteria that are drawn from 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 criteria for stability 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 (2) is 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 (see Appendix G for a summary of the approach used to develop the waste classification limits in 10 CFR 61.55). 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 approaches, 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 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.

8.2.1 Acceptable Waste Characterization Methods

Licensees shall specify methods for adequately characterizing waste for the purposes of demonstrating that the 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 methods shall identify the characterization parameters and acceptable uncertainty in the characterization data. 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. The disposal facility operator should ensure that the generator’s characterization is close enough in time to when the demonstration that waste meets the acceptance criteria is performed, such that the waste stream characteristics have not changed. 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).

8.2.1.1 *Acceptable Methods for Characterizing Activities and Concentrations*

The first step in characterizing the waste is to determine the activities and concentrations of radionuclides in the waste that have allowable limits for acceptance. 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 WCWF (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 that 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 is included in "NRC Regulatory Issue Summary 2015-02, Reporting Of H-3, C-14, Tc-99, And I-129 On The Uniform Waste Manifest" (NRC, 2015b). The BTP WCWF 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. 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 helpful, by applying 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 8-6), including, but not limited to, the following:

- a sample's representativeness, 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

8.2.1.1.1 Characterization Methods for Criteria Based on the Waste Classification Requirements

The BTP WCWF provides guidance on the use of various methods to determine concentrations to demonstrate that allowable concentrations developed from 10 CFR Part 61 waste classification requirements are met (NRC, 1983d). The BTP WCWF indicates that the NRC

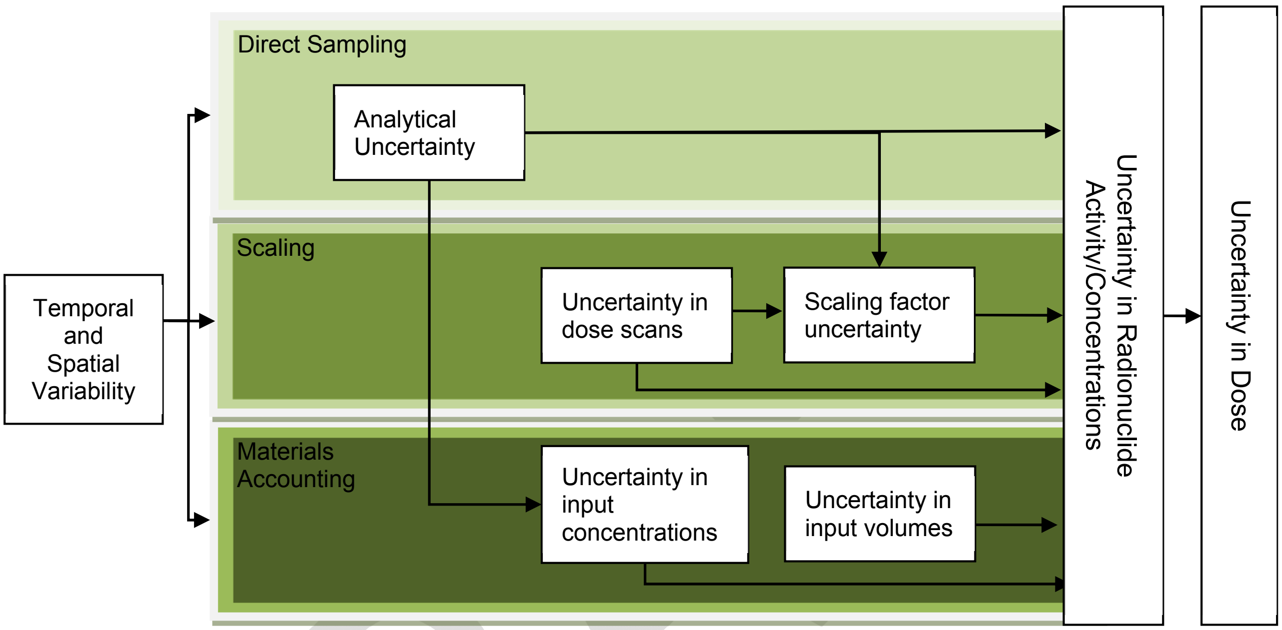

Figure 8-6 Sources of Uncertainty in Various Methods of Determining Radionuclide Activities or Concentrations in Waste Packaged for Disposal

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. Licensees should reflect uncertainty in radionuclide activities and concentrations in the technical analyses.

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, 2015a). The 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 BTP CA considers the intruder receptor scenarios described in Section 4.2 of this document in developing guidance on acceptable averaging approaches (NRC, 2015a). However, the BTP CA also considers receptor scenarios in which an individual may be exposed to discrete items. For instance, the NRC staff considered a waste-handling receptor scenario to develop the BTP CA for disposal of discrete sources, which is not discussed in this guidance for intruder assessments (NRC, 2015a). The NRC staff used these receptor scenarios to develop

the BTP CA for limiting the range of waste concentrations that can be mathematically averaged in a single container. The BTP CA provides specific guidance on appropriate waste volumes over which concentrations should be averaged for waste classification by waste generators or processors (NRC, 2015a).

This guidance, as opposed to the guidance in the BTP CA (NRC, 2015a), focuses on determining appropriate concentrations to use in site-specific inadvertent 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 of this guidance), although conservative assumptions are appropriate.

8.2.1.1.2 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 identification of defense-in-depth protections. Licensees should identify significant waste-related parameters of the analyses as criteria for waste acceptance. 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. 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 8.2.1.1, 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 WCWF provides guidance on the use of various methods to determine concentrations to demonstrate that allowable concentrations developed from 10 CFR Part 61 waste classification requirements are met (NRC, 1983d). The BTP CA is also available to licensees (NRC, 2015a). 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

WCWF (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 WCWF (NRC, 1983d) is appropriate or inappropriate depending upon whether it is included or excluded.

8.2.1.2 *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 WFTM (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). The disposal facility operator should identify which quality-related parameters need to be controlled, including 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.

8.2.2 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 shown in Figure 8-7) 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 8-7 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.
7. Develop the plan for obtaining data.

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.

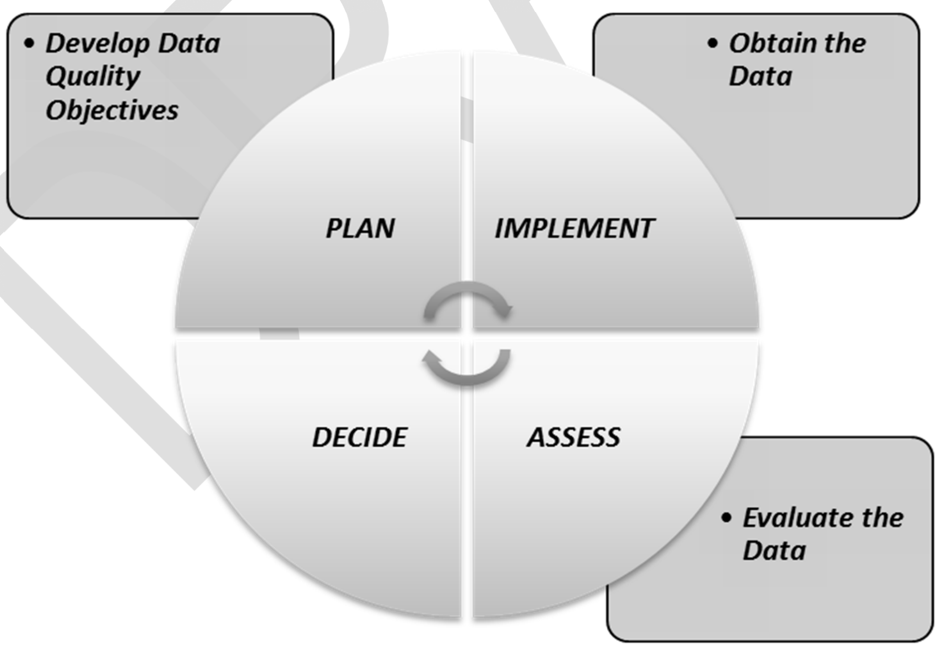

Figure 8-7 Data Life Cycle Framework for Waste Characterization

DQOs should be qualitative or quantitative statements that satisfy the following:

- clarify the characterization objective
- define the most appropriate type of data to collect
- determine the most appropriate conditions for collecting the data
- specify limits on decision errors that will be used as the basis for establishing the quantity and quality of data needed to 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.

8.2.3 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, the importance of the waste streams to demonstrating that the performance objectives are met, and whether it supports the capabilities of defense-in-depth protections identified by the licensee. The elements of the documentation should 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. Section 9.1 of NUREG-1200 provides guidance on acceptable QA programs (NRC, 1994).

- **Procedures**. 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. Section 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 8.3). 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.

8.3 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 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
- provide approaches for managing certified waste to maintain its certification status

8.3.1 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 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.

8.3.1.1 *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.

8.3.1.2 *Certification Procedures*

Licensees should implement the certification program through the use of documented processes and procedures. A certification program is used to 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 8.2. 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 8.3.2. 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. Section 4.1 of NUREG-1200 (NRC, 1994) provides guidance on developing adequate procedures for receipt and inspection of waste arriving at a disposal facility. Section 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.

8.3.1.3 *Certification Documentation*

The key document in the waste certification process 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 with respect to demonstrating the waste acceptance criteria have been met and that the waste can be certified as acceptable.

- **Waste Stream Profile**. The waste stream profile is a description of the source, physical and chemical description, and upper limits on radionuclides of the waste stream.

- **Radionuclide Content**. Radionuclide content includes the concentration and inventory of radionuclides determined from waste characterization. See Section 8.2 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.

- **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).

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- **Quality Assurance Records**. QA records may include documentation of testing or inspections required for waste certification. 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 8.3.2.

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.

8.3.1.4 *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. Section 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.

8.3.2 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.

8.4 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 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 defense-in-depth protections identified by the licensee will be adequate, 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 both the amended criteria and the supporting technical analyses that demonstrate the performance objectives will be met to the regulator as part of a request for amendment to their 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).

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9.0 SITE CLOSURE

Site closure and stabilization means those actions that are taken upon completion of operations that prepare the disposal site for custodial care and that ensure that the disposal site will remain stable and will not need ongoing active maintenance. Site closure occurs after the disposal site is no longer receiving waste for disposal.

9.1 Closure Process

A licensee is required to file an application for closure in accordance with 10 CFR 61.20 and 10 CFR 61.28. Prior to final closure of the disposal site, licensees are required by 10 CFR 61.28(a) to submit an application to amend the license for closure. The closure application must include a final revision of the safety case and specific details of the disposal site closure plan that was included as part of the license application submitted under 10 CFR 61.12(g). The closure 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 closure plan must include "the results of tests, experiments, or any other analyses relating to backfill of excavated areas, closure and sealing, waste migration and interaction with emplacement media, or any other tests, experiments, or analysis pertinent to the long-term containment of emplaced waste within the disposal site, including revised analyses for 10 CFR 61.13 and updates to the identified defense-in-depth protections using the details of the submitted site closure plan and waste inventory."

Under 10 CFR 61.28(c), the NRC can only authorize closure of the LLW land disposal facility if there is reasonable assurance that the long-term performance objectives of subpart C will be met. Licensees are required to take additional action prior to site closure to ensure that the LLW that has already been disposed, including significant quantities of long-lived radionuclides and other LLW streams that were not analyzed in the original 10 CFR Part 61 regulatory basis, will meet the performance objectives of Subpart C.

The requirement to update the technical analyses at closure is designed to ensure that:

- The final inventory that has been disposed is reflected in the analyses.
- The final analyses are consistent with monitoring data collected to date.
- The final closure plan design is evaluated in the analyses.
- New scientific and technical information that was developed during operations is reflected in the analyses.

Depending on the significance of the changes between the last revision of the technical analyses and the technical analyses at closure, the level of effort and associated documentation that a licensee would need to develop could be minimal. If the initial analyses of the facility appropriately accounted for all the changes observed during operations, then the licensee may submit documentation justifying that the initial analyses is sufficient. Given that most facilities will operate for multiple decades, this circumstance is expected to be rare and a regulator should review the basis for the assertion carefully. In most cases, it is appropriate for a licensee to document the changes between previous and final technical analyses and to demonstrate the impact of those changes by revising the analyses. If there are numerous and substantial changes, such as significant revisions to the conceptual models, a new engineered closure

design, and new waste streams in the inventory, then a full revision to the analyses is recommended, including revision of the documentation of the technical analyses. In all cases, the final closure analyses documentation should describe the final inventory at closure and list the quantities of all isotopes that have been disposed.

Upon review and consideration of the application for closure, the regulator will issue an amendment authorizing closure if there is reasonable assurance that the long-term performance objectives in 10 CFR Part 61 will be met. The licensee then must maintain a period of post-closure observation and maintenance for five years to carry out necessary maintenance and repairs until the license is transferred to the disposal site owner. The period of post-closure observation may be shorter or longer than five years. The exact period of time is the period of time necessary to confirm that closure activities have not introduced instability to the site, which may differ from site to site.

After the post-closure period, the licensee may apply to transfer the license to the disposal site owner. Transfer of the license will occur if the regulator determines that:

1) the closure plan has been properly implemented,
2) reasonable assurance has been provided that the performance objectives have been met,
3) funds for care and necessary records have been transferred to the disposal site owner,
4) a post-closure monitoring program is operational for implementation by the disposal site owner, and
5) the Federal or State government agency which will assume responsibility for institutional control is prepared to assume control and ensure the institutional control requirements will be met.

9.1.1 Institutional Controls

Institutional control is described in 10 CFR 61.59(b). The institutional control program must be developed to physically control access to the disposal site following transfer of control from the licensee to the disposal site owner. The institutional control program must provide for environmental monitoring, periodic surveillance, minor custodial care, or other requirements and conditions provided by the regulator. The institutional control program must provide for the administration of funds to cover the costs of the activities.

The period of institutional controls may not be relied upon (in developing the technical analyses demonstrating the performance objectives will be met) for more than 100 years following transfer of control from the licensee to the site owner. However, the period of institutional controls that is implemented will be determined by the regulator. It may be shorter or longer than 100 years.

The post-closure institutional control must be adequate to ensure with reasonable assurance that protection of public health and safety in accordance with the performance objectives in 10 CFR 61.41 and 10 CFR 61.42 will be provided. In addition, the post-closure institutional controls must provide reasonable assurance that long-term stability of the disposed waste and the disposal site will be achieved and will eliminate the need for ongoing active maintenance.

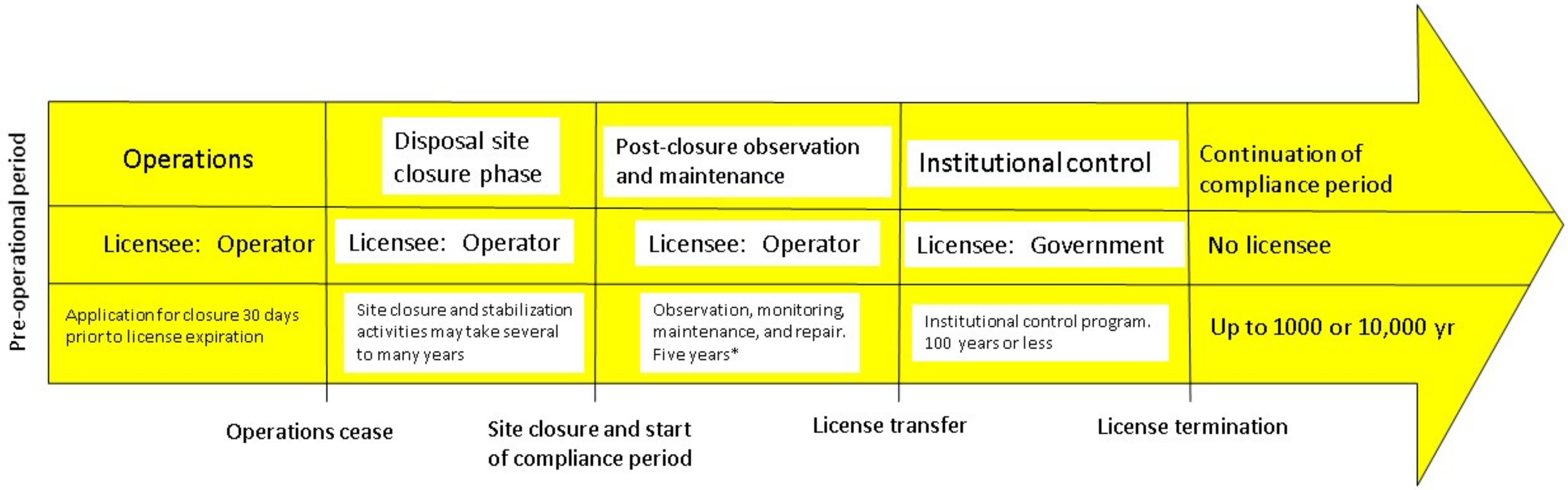
After the institutional control period, the license may be terminated if the institutional control requirements have been met and if any additional requirements (e.g., resulting from new information developed during the institutional control period) have been met. In addition, permanent markers warning against intrusion must be installed. Figure 9-1 shows the timeline from operation of a LLW disposal facility until termination of its license.

9.1.2 Permanent Markers

The placement of permanent markers warning against intrusion is required in 10 CFR 61.31(c)(2). The inadvertent intruder analyses required to meet the performance objective in 10 CFR 61.42 and the development of waste acceptance criteria are the primary means to ensure protection of public health and safety after closure of the disposal facility. As an extra layer of defense, markers can be used to deter future use of the site; however, the markers themselves should not be relied upon as engineered barriers. Most of the hazard to an inadvertent intruder will be associated with short-lived radionuclides (e.g., Cs-137 and Sr-90). Therefore, while it is desirable to make markers that are as durable and permanent as possible, the permanence of markers is not as important for LLW disposal sites as compared to a HLW repository.

Based on the siting guidelines, most LLW disposal facilities will be in areas of low population density. Markers should warn someone of the potential for danger should they disturb the site, but also should not invite disturbance due to curiosity or investigation. The following guidelines may be considered for the development of permanent markers for a commercial LLW disposal facility in the United States:

- There are no requirements for how long the markers must last. Markers should be designed to last as long as practicable based on information available when they are designed.
- Materials used should have little intrinsic value and should provide minimal incentive for disturbance or theft of the markers.
- Marker design should consider the site environment and projected future site environment. Markers should be durable and be visible for the timeframes desired.
- The marking system must be cross-cultural to the extent possible, but multiple languages are not necessary.
- Different types of markers (detailed vs. simple, different material types) may be useful.
- Markers should communicate basic cautionary information – “Something manmade is here and it is dangerous.”
- Markers should be large enough to inhibit movement by erosion or theft.
- Markers should be placed on each boundary of the site.



Not to scale
* The Commission may approve shorter or require longer periods if conditions warrant

Figure 9-1 Timeline from Operations until Termination of License

Some of the markers should be simple such as the example provided in Figure 9-2, which combines symbols and simple language to convey there is danger to someone digging in the area. Simple markers may be combined with more detailed markers that explain there is radioactive material buried and it should not be disturbed. However, the detailed text may degrade over time or may no longer be understood.

Figure 9-2 Example of Simple Warning Marker

Figure 9-3 is an example from Plot M at a closed burial area of the world's first nuclear reactors in Illinois near Argonne National Laboratory. A marker was also employed at the location of the Project Gnome nuclear test in New Mexico. Each of these markers has been subject to vandalism since placement. In the case of the Project Gnome marker, the marker has been moved several meters over time as it is used by grazing cattle as a scratching post.

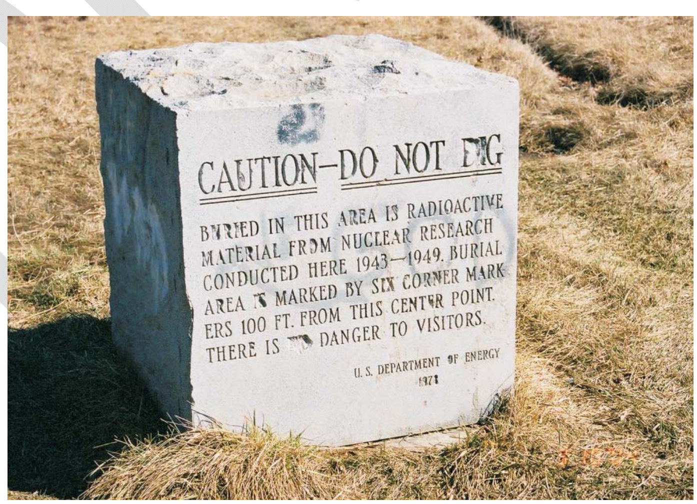


Figure 9-3 Marker at Plot M in Illinois

9.1.3 Financial Assurance

Financial assurance are the mechanisms through which a licensee demonstrates that funds will be available to cover the necessary costs of conducting all licensed activities over the planned operating life of the project. Subpart E of 10 CFR Part 61 contains the financial assurance requirements for land disposal of radioactive waste. A licensee must demonstrate that they possess the necessary funds or have reasonable assurance of obtaining the necessary funds (or a combination of the two). Though the requirement applies to the full life cycle of the project, this section emphasizes funding for closure and stabilization.

The requirements for assuring funding of disposal site closure and stabilization operations are found in 10 CFR 61.62. The assurances are to be based on Commission approved cost estimates reflecting the Commission approved plan for disposal site closure and stabilization. The cost estimate must take into account the total capital costs incurred if an independent contractor were hired to perform the closure and stabilization work. The applicant should provide a detailed breakdown including an explanation of the assumptions used in the cost estimate. The licensee should develop a closure plan that eliminates the need for ongoing active maintenance to the extent practicable and ensures only minor custodial care, surveillance and monitoring are necessary.

Additionally, 10 CFR 61.62 contains the surety arrangement requirements necessary for disposal site closure and stabilization. The applicant should identify the source(s) for the funds necessary to pay the cost of closure and stabilization.

The regulator should review the surety annually to ensure sufficient funds are available for completion of the closure plan by an independent contractor. The surety amount should change based on inflation, increases in the amount of disturbed land, changes in engineering plans and any other conditions affecting costs. However, because the surety should be based on the life cycle of the facility, the surety should not be limited to considering only the amount of land disturbed to date but the current estimate for total disturbance (and total waste volumes and activities to be disposed) over the life of the facility. The types of engineered designs used on the disposal facility closure design will also impact the surety. Higher reliance on engineered designs to achieve the regulatory requirements will have higher relative surety than lessor reliance on engineered designs.

10 CFR 61.63 contains the financial assurance requirements for institutional controls. Prior to issuance of the license, the applicant is required to provide for review and approval a binding agreement between the applicant and the disposal site owner that ensures sufficient funds will be available to cover cost of monitoring and maintenance during the institutional control period. Monitoring will include radiological monitoring, as well as, non-radiological monitoring to ensure the barriers being relied upon are functioning as well or better than represented in the technical analyses. The institutional control period that may be relied upon in the technical analyses is up to 100 years. However, a licensee may adopt a longer institutional control period. The financial assurance provided by the licensee must be consistent with the institutional control period used. The binding agreement will be reviewed periodically by the regulator to ensure changes in inflation, technology and disposal facility operations are reflected in the arrangement.

9.2 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 10 CFR Part 61 performance objectives are met before disposal site closure. 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, the NRC staff believes that the elements of a performance confirmation program are supported by 10 CFR Part 61 (e.g., 10 CFR 61.7(c)(3)), as shown in Table 9-1.

Table 9-1 Regulatory Requirements Supportive of Performance Confirmation

Section	Requirement
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

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 larger the amount of information collected for performance confirmation, the stronger the basis will be for approval of the final closure of the site.

As discussed in Section 9.1, licensees are required under 10 CFR 61.28 to update technical analyses (e.g., performance assessment, inadvertent intruder assessment, site stability evaluation, and performance period analyses) at closure. A performance confirmation program can be used to proactively generate information to support this update, in particular, the most risk-significant and uncertain elements of the technical analyses.

In addition, it is good practice for a licensee to update the technical analyses supporting licensing 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 8.4 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 of the license.

A licensee 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). Several of the possible conditions that could trigger a decision to update waste acceptance criteria, and therefore, to update technical analyses, may include the following:

- substantially different inventory than anticipated (e.g., quantity, concentration, form)
- new site information (e.g., environmental conditions, characterization data)
- new information on engineered barrier performance or other defense-in-depth protections
- monitoring data that are inconsistent with current analyses
- substantial changes to relevant scientific understanding
- 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.

9.3 Mitigation

In some cases, the licensee operating 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 describes when licensees should consider mitigation, what information they should

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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 unacceptable 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 also 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 benefits of the proposed remedial action outweigh any negative impacts.

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10.0 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 10-1, 10-2, and 10-3 present references according to the performance objectives in 10 CFR Part 61. Table 10-4 provides a list of general topics and associated references. Table 10-5 and Table 10-6 provide references for wasteforms and release and transport modeling, respectively. 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 10-1 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

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Table 10-2 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 10-2 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
NUREG-1757, "Consolidated Decommissioning Guidance" (NRC, 2006)	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
	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

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Table 10-3 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 10-4 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)
Modeling Climate and Infiltration	NUREG-1573, Section 3.3.3 (NRC, 2000a) NUREG-1854, Section 4.3.1 (NRC, 2007a)

Table 10-4 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-Activated 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)
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)

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Table 10-4 Guidance Crosswalk by Topic

Topic	Document
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, 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)

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Table 10-4 Guidance Crosswalk by Topic

Topic	Document
Climate and Infiltration Modeling	NUREG-1573, Section 3.3.3 (NRC, 2000a) NUREG-1854, Section 4.3.1(NRC, 2007a)
Biosphere Characteristics and Dose Modeling	NUREG-1573, Section 3.3.7 (NRC, 2000a) NUREG-1854, Section 4.3.5 (NRC, 2007a)
Transport Modeling	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)
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)

Table 10-4 Guidance Crosswalk by Topic

Topic	Document
Defense-in-Depth	NUREG/KM-009, "Historical Review and Observations of Defense-in-Depth," (NRC, 2016) U.S. Nuclear Regulatory Commission, "Risk-Informed Decision Making for Nuclear Material and Waste Applications," February 2008, ADAMS Accession No. ML080720238
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) 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)

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Table 10-4 Guidance Crosswalk by Topic

Topic	Document
	NUREG-1623, "Design of Erosion Protection for Long-Term Stabilization," (NRC, 2002b)

Table 10-5 Additional References on Wasteforms and Release

Description	Reference
Provides acceptable methods to demonstrate waste stability requirements. Performance confirmation and qualification testing for cement stabilized wasteforms are described.	NRC, 1991b. U.S. Nuclear Regulatory Commission, Technical Position on Waste Form, Rev. 1, Washington, DC, January 18, 1991, ADAMS Accession No. ML033630746
Provides an examination of the geochemical aspects of radioactive waste disposal. Chapter 12 provides a summary of different types of wasteforms including compiled performance data.	Brookins, 1984. Brookins, D.G., *Geochemical Aspects of Radioactive Waste Disposal*, Springer-Verlag, New York, NY, 1984
Provides a literature review and assessment of the factors affecting release from grouted systems.	Pabalan, 2009. Pabalan, R.T. et al, "Review of Literature and Assessment of Factors Relevant to Performance of Grouted Systems for Radioactive Waste Disposal," Center for Nuclear Waste Regulatory Analyses, CNWRA 2009-001, April 2009.
Provides data and discussion on release rates and test methods to estimate the long-term performance of cement and slag wastes (test method discussion and examples are applicable to many types of wasteforms that may be used for low-level waste disposal).	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.
Provides discussion and comparison of laboratory and field leach test results with consideration of the factors relevant to translating from different time and spatial scales.	NRC, 2011. U.S. Nuclear Regulatory Commission (Ebert, W.L.), "Radionuclide Release from Slag and Concrete Waste Materials Part 2: Relationship Between Laboratory Tests and Field Leaching," NUREG/CR-7105, Argonne National Laboratory, Argonne, IL, October 2011.
Provides a literature review of radionuclide chelating agents that may be found in low-level waste.	Serne, 1996. Serne, R.J. et al, "Characterization of Radionuclide-Chelating Agent Complexes Found in Low-Level Radioactive Decontamination Waste," U.S. Nuclear Regulatory Commission, NUREG/CR-6124, March 1996

Table 10-5 Additional References on Wasteforms and Release

Description	Reference
Discusses the potential for microbial degradation of low-level radioactive waste.	Rogers, 1996. Rogers, R.D. et al, “Microbial Degradation of Low-Level Radioactive Waste,” U.S. Nuclear Regulatory Commission, NUREG/CR-6341, June 1996
Provides a test method to measure the leaching of solidified wastes (results can be sensitive to test interval).	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).
Provides a test method to measure diffusive releases from solidified wastes.	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.
Provides a summary of wasteform testing in chapter 5 and a discussion of various test method in an appendix to chapter 5. Discussion of wasteform performance (focused on high-level waste) is provided in chapter 7.	National Research Council, 2011, “Waste Forms Technology and Performance: Final Report,” The National Academies Press, 2011.
Provides a detailed discussion of glass corrosion and processes including field testing and observations of natural glasses. A list of test methods is provided in table 1-2. International experience is summarized in appendix B.	DOE, 1994, “High-Level Waste Borosilicate Glass: A Compendium of Corrosion Characteristics, Volume II,” J.C. Cunnane (editor), US Department of Energy, March 1994.
Provides discussion of methods used to estimate container performance as well as different equations and methods to represent waste release.	Sullivan, 2004. Sullivan, T., “Waste Container and Waste Package Performance Modeling to Support Safety Assessment of Low and Intermediate-Level Radioactive

Table 10-5 Additional References on Wasteforms and Release

Description	Reference
	Waste Disposal," BNL-74700-2005-IR, Brookhaven National Laboratory, June 2004.
Provides an example of using modern performance assessment software to execute a legacy model of waste release.	Mattie, 2007. Mattie, P.D. et al, "A User's Guide to the GoldSim/BLT-MS Integrated Software Package: A Low-Level Radioactive Waste Disposal Performance Assessment Model," SAND2007-1354, Sandia National Laboratories, March 2007.
Provides a comprehensive source of conference papers on all types of wasteform experiments, observations, assessment, and modeling.	Materials Research Society Symposium Proceedings (numerous over multiple decades)

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Table 10-6 Additional References on Transport Modeling

Topic[2]	Description	Reference
UZ	Chapter 10 provides a summary of contaminant transport considerations for the unsaturated zone.	Tindall, 1999. J.A. Tindall and J.R. Kinkel, *Unsaturated Zone Hydrology for Scientists and Engineers*, Prentice Hall, Upper Saddle River, NJ, 1999.
UZ	Section 5.5 covers unsaturated zone flow and transport.	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.
UZ	Discusses the application of groundwater models	NAS/NRC, 1990. National Academy of Sciences/National Research Council, *Ground Water Models: Scientific and Regulatory Applications,* National Academy Press, Washington, DC, 1990.
SZ	Chapter 4 discusses analysis of groundwater transport of radionuclides.	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.
SZ	General text on groundwater hydrology and transport.	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.
SZ	Provides a compilation of distribution coefficients for four major soil types.	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.

[2] UZ = unsaturated, SZ = saturated, SW = surface water, AT = atmospheric, BT = biotic

Table 10-6 Additional References on Transport Modeling

Topic[2]	Description	Reference
SZ	Text describing groundwater hydrology.	Bear, 1979. Bear, J., *Hydraulics of Groundwater,* McGraw-Hill, New York, NY, 1979.
SZ	Provides parameter estimation of saturated zone properties. Provides a comparison of numerical modeling with analytical modeling results.	Talbot, 1994. Talbot, M.E. and G.W. Gelhar, "Auxiliary Analyses in Support of Performance Assessment of a Hypothetical Low-Level Waste Facility: Groundwater Flow and Transport Simulation," US Nuclear Regulatory Commission, NUREG/CR-6114, Vol. 3, May 1994.
SW	Covers multiple concepts and provides observations of transport of radionuclides in surface water.	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.
SW	Provides screening models for surface water transport of radionuclides.	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.
SW	Provides analytical methods for estimating dispersion of radionuclides in different types of surface water bodies.	NRC, 1977. Regulatory Guide 1.113 – Estimating Aquatic Dispersion of Effluents from Accidental and Routine Reactor Releases for the Purpose of Implementing Appendix I, US Nuclear Regulatory Commission, April 1977.

Table 10-6 Additional References on Transport Modeling

Topic[2]	Description	Reference
AT	Covers multiple concepts and provides observations of transport of radionuclides in the atmosphere.	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.
AT	Provides comparisons of different atmospheric modeling codes and methods.	NRC, 2004. US Nuclear Regulatory Commission (Molenkamp, C.R. et al), "Comparison of Average Transport and Dispersion Among a Gaussian, a Two-Dimensional, and a Three-Dimensional Model," NUREG/CR-6853, Pacific Northwest National Laboratory, Richland, WA, October 2004.
AT	Provides a description of a radiological assessment tool used for nuclear accidents.	NRC, 2001 (Sorjeen, A.L. et al), "RASCAL 3.0: Description of Models and Methods," NUREG-1741, US Nuclear Regulatory Commission, March 2001.
AT	Provides a description of a radiological assessment tool used for nuclear accidents.	NRC, 2012 (Ramsdell, J.V. et al), "RASCAL 4.0: Description of Models and Methods," NUREG-1940, US Nuclear Regulatory Commission, December 2012.
BT	Discusses the importance of biotic pathways with respect to radioactive waste disposal.	NRC, 1982. 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.

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Table 10-6 Additional References on Transport Modeling

Topic[2]	Description	Reference
BT	Provides numerous references and discussion of biological processes impacting release and transport.	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.

Additional web resources

The following web links provide additional information on radionuclide transport that may be useful to stakeholders. As of July 2016, these website addresses are valid; over time, these addresses may no longer be accurate due to the fluid nature of the Internet. The NRC staff recommend going to the highest level of these web links to find the information, if the actual link does not work (e.g., www.usgs.gov).

http://groundwater.ucdavis.edu/Materials/Vadose_Zone_Modeling__Web-Links/ (UZ modeling)

http://igwmc.mines.edu/software/category_list.html (software list)

http://water.usgs.gov/software/lists/groundwater/ (software list)

http://water.usgs.gov/software/lists/surface_water/ (surface water software)

https://www.usnrc-ramp.com/ (radiological protection codes and analysis)

11.0 REFERENCES

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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.

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12.0 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, an 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.

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 probable future 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 but will include disruptive processes.

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 from the completion of site closure to 1,000 years after site closure for disposal sites that do not contain significant quantities of long-lived radionuclides. For disposal sites that contain or plan to accept significant quantities of long-lived radionuclides, the compliance period ends at 10,000 years after closure of the disposal site.

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.

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 wasteforms, intruder barriers, resistive covers, and evapotranspiration or water balance covers.

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 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 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).

Inadvertent 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 that 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 ten percent of the initial activity of the radionuclide remains after 1,000 years, (2) where the peak activity from

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progeny occurs after 1,000 years, or (3) where more than ten percent of the peak activity of a radionuclide (including progeny) within 1,000 years remains after 1,000 years. The first part of the definition represents radionuclides with approximately a 300-year or longer half-life. Examples of isotopes that are short-lived but produce long-lived progeny are Am-241 and Cm-242.

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 disposal 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 compliance 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 significant quantities of long-lived waste. 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 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.

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 the behaviors and activities of the people who may be 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 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 subset of important FEPs that are used to identify a probable future evolution of the disposal site.

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 ensure 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.

Validation (software): Verification that the governing equations accurately describe the physical processes that occur.

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

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code ensures that the computer program accurately solves the equations that constitute the mathematical model.

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.

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APPENDIX A
CHANGES TO 10 CFR PART 61 PERFORMANCE OBJECTIVES MADE IN 2017 RULEMAKING

	Former 10 CFR Part 61 regulations	Revised 10 CFR Part 61 regulations
Protection of the general population from releases of radioactivity (10 CFR 61.41)	- Pathway analysis - Undefined period of performance - 0.25 mSv (25 mrem) annual whole body dose limit for the protection of the general population from releases of radioactivity - ALARA concept	- Performance assessment that estimates peak annual dose that occurs within the compliance period - 0.25 mSv (25 mrem) annual dose limit for the protection of the general population from the releases of radioactivity that occurs within the compliance period - ALARA concept - Analyses that demonstrate releases will be minimized to the extent reasonably achievable for the protection of the general population beyond the compliance period - Performance period analyses that only apply for disposal sites containing significant quantities of waste with long-lived radionuclides - Analyses that demonstrate how the disposal site has been designed to limit long-term releases.
Protection of individual from inadvertent intrusion (10 CFR 61.42)	- Comply with § 61.55 LLW classification and segregation requirements - Provide adequate barriers to inadvertent intrusion - Undefined compliance period - No annual dose limit	- Inadvertent intruder assessment that estimates peak annual dose that occurs within the compliance period - 5 mSv (500 mrem) annual dose limit - Analyses that demonstrate exposures will be minimized to the extent reasonably achievable for the protection of inadvertent intruders beyond the compliance period. - Performance period analyses that only apply for disposal sites containing significant quantities of waste with long-lived radionuclides - Analyses that demonstrate how the disposal site has been designed to limit long-term exposures to an inadvertent intruder.
Stability of the disposal site after closure Long-term analyses (10 CFR 61.44)	Analyses of active natural processes that demonstrate that there will not be a need for ongoing active maintenance of the disposal site following closure	Analyses of active natural processes that demonstrate 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 during the compliance period

APPENDIX B
HAZARD MAPS

The NRC staff created hazard maps related to the features and phenomena of 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.

Preparation of the hazard maps:

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.

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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)

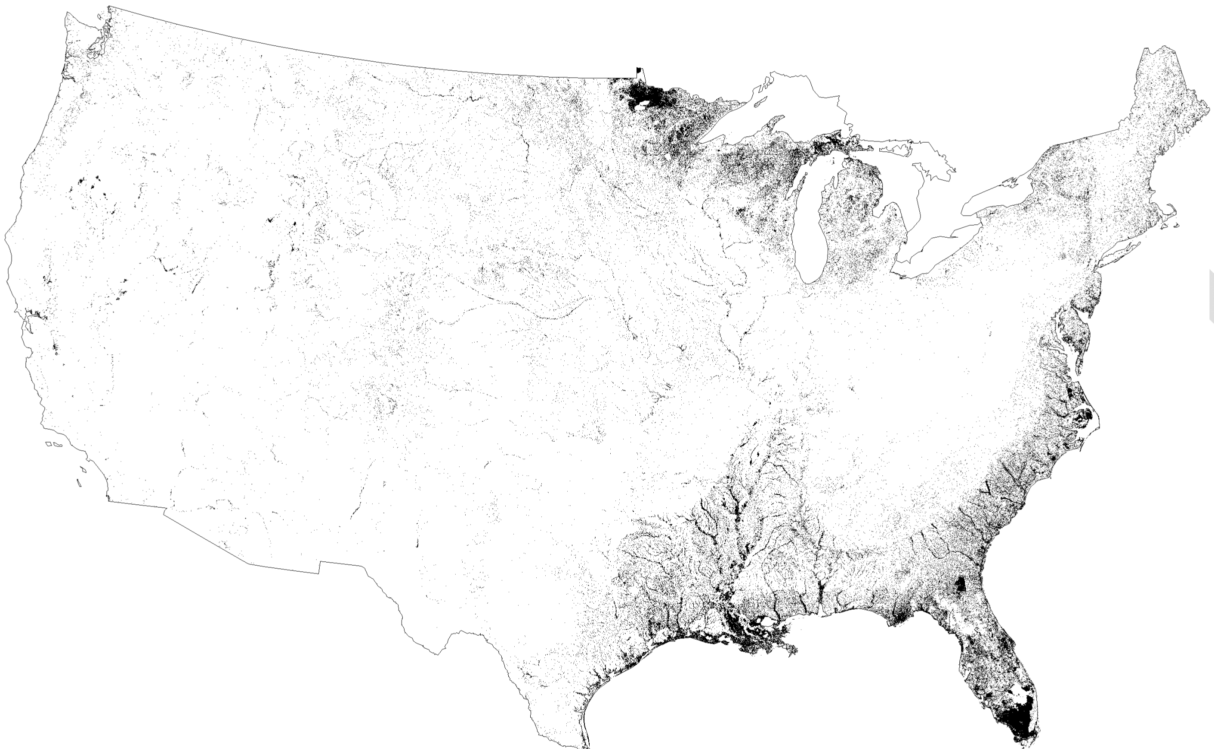

Figure B-2: Approximate area of current wetlands. Proposed sites located near these areas may require additional site characterization and analysis. Wetland areas in the future may change (USGS, 2011)

Figure B-3: Areas of potential flooding that may require additional site characterization and analysis (FEMA, 2012; FEMA, 1998; ESRI, 2008a; ESRI, 2008b)

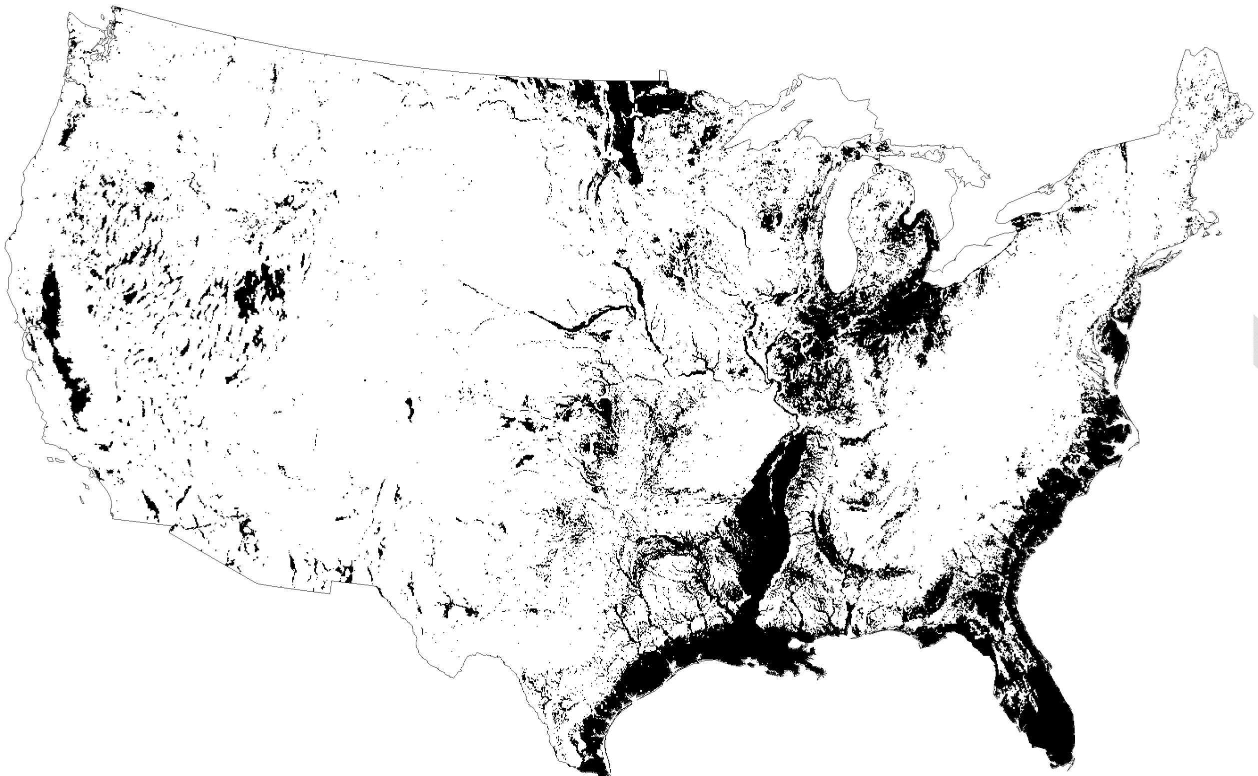

Figure B-4: Approximate area of simulated current water tables shallower than 30 m. Proposed sites located in these areas may require additional site characterization and analysis. Future near-surface groundwater areas may change (Kreakie et al, 2012)

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)

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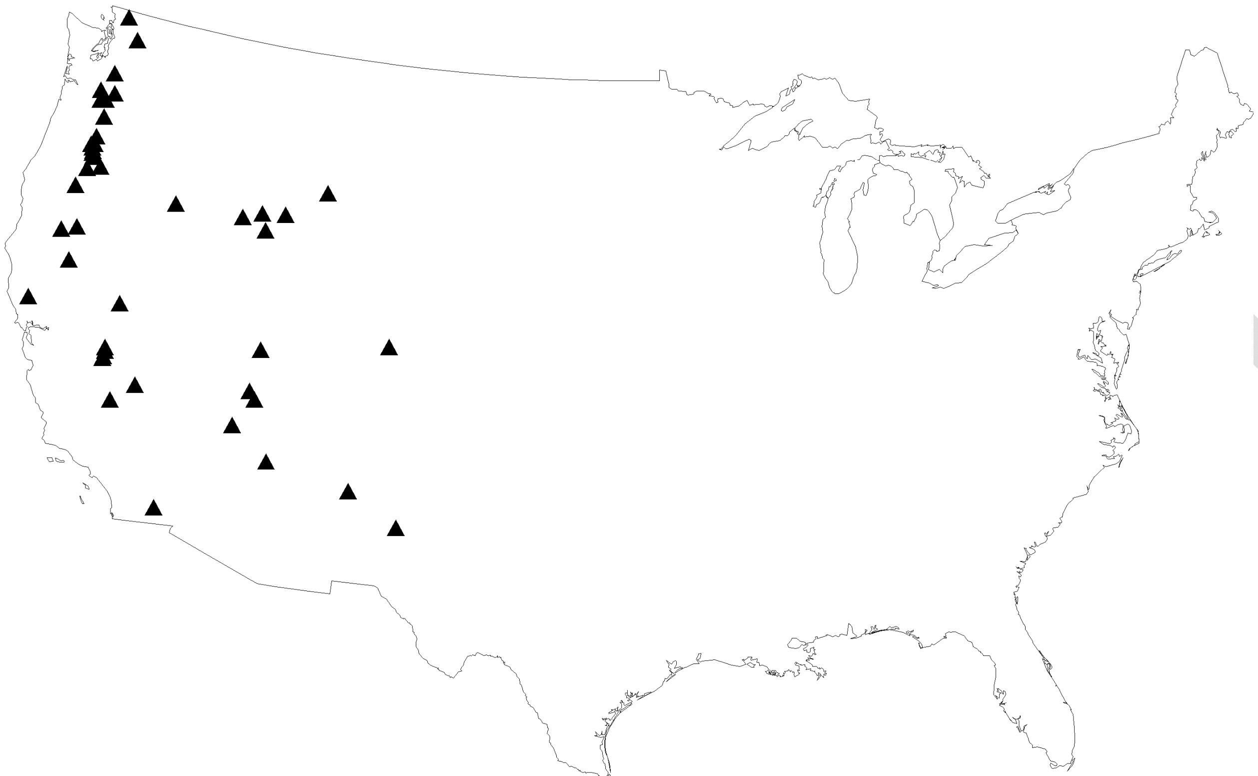

Figure B-6: Approximate locations of Holocene volcanic activity. Proposed sites located near these locations may require additional analysis and evaluation (Siebert and Simkin, 2002)

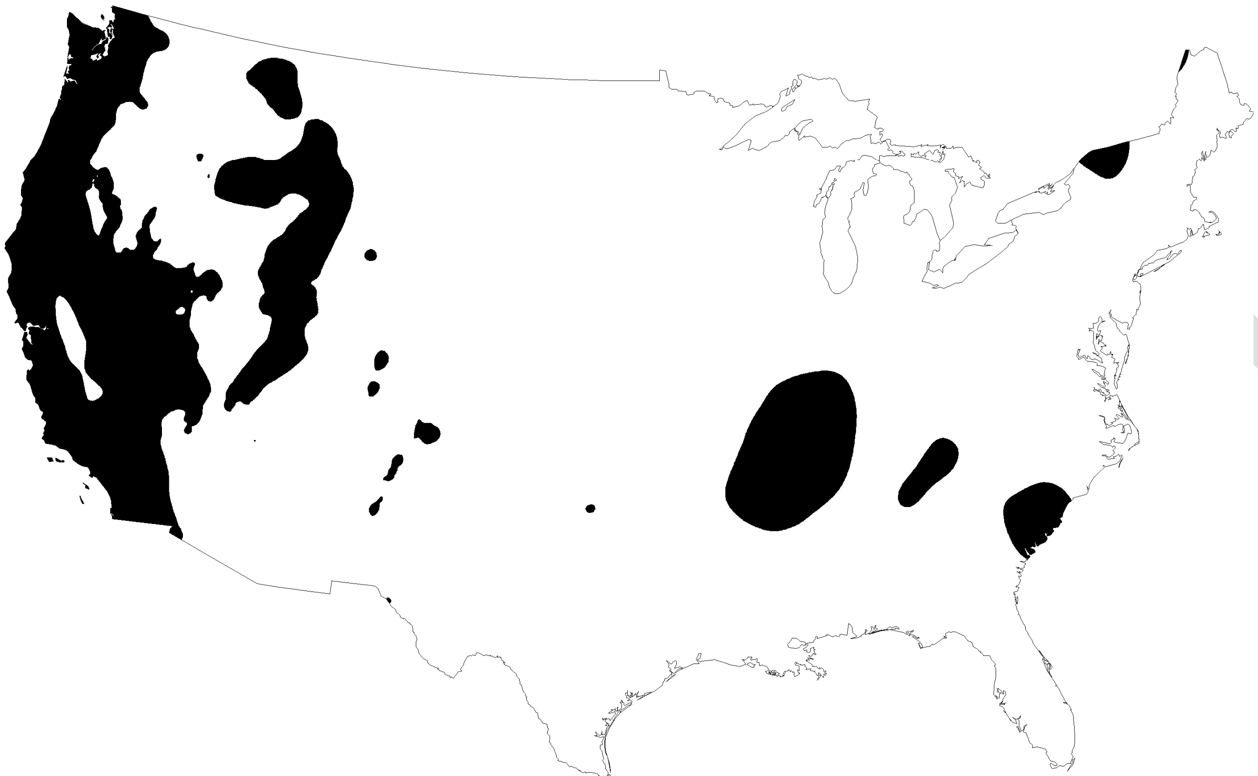

Figure B-7: Current approximate areas of higher potential seismic hazard. Proposed sites located near these areas may require additional analysis and evaluation (Petersen et al, 2011)

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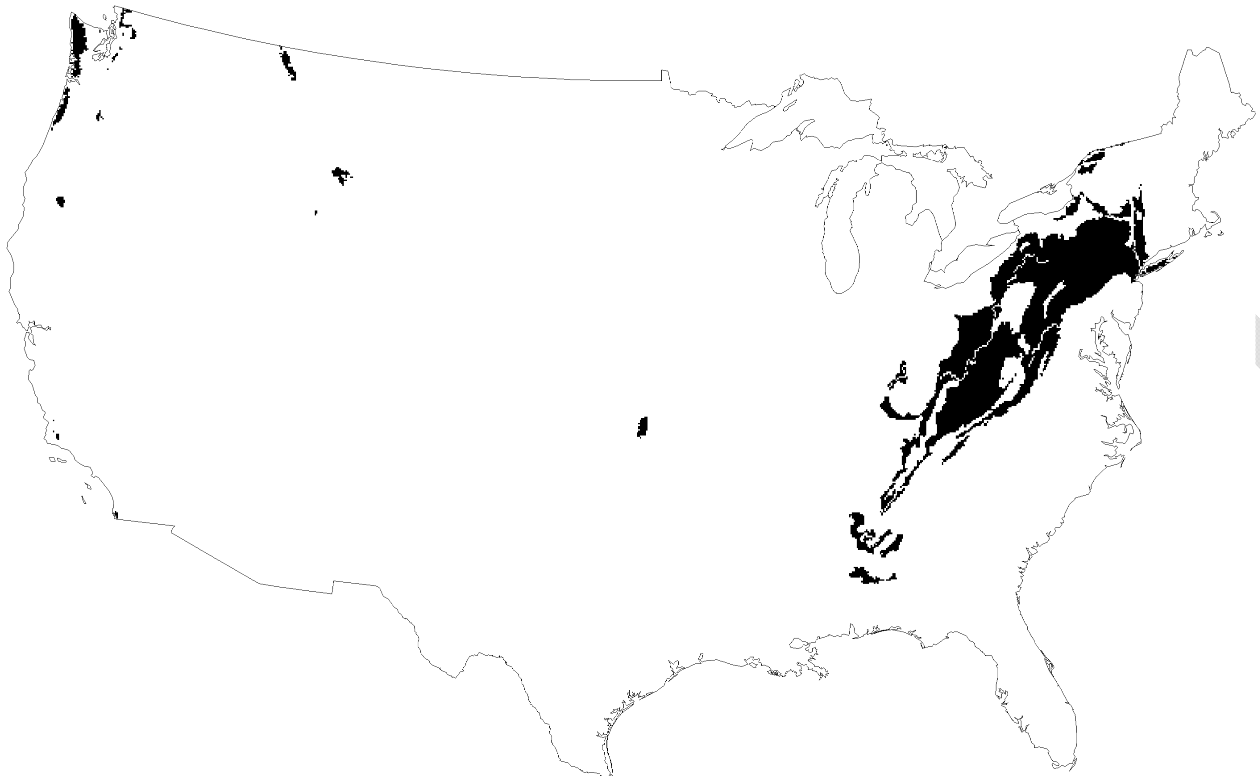

Figure B-8: Current approximate areas of higher vulnerability to water erosion. Proposed sites located in these areas may require additional site characterization and analysis. Areas of high vulnerability to water erosion in the future may change (USDA, 1988)

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)

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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]

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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 should 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 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 meteorology
	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)

Table C-1 Starter FEPs List for Near-Surface Disposal in the United States

Type	FEP
	Temperature cycling or extremes Freeze thaw cycling 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., desiccation) 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, bioturbation, 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

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Table C-1 Starter FEPs List for Near-Surface Disposal in the United States

Type	FEP
	Geomorphology
	Surface geologic processes – mass wasting, subsidence, slope failure, etc.
	Dynamic change to geology (e.g., sinkhole formation)
	Loading and differential settlement
	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 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

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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 Europe[1]. A brief description of each of these data sources is provided.

BIOMOVs II
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 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.

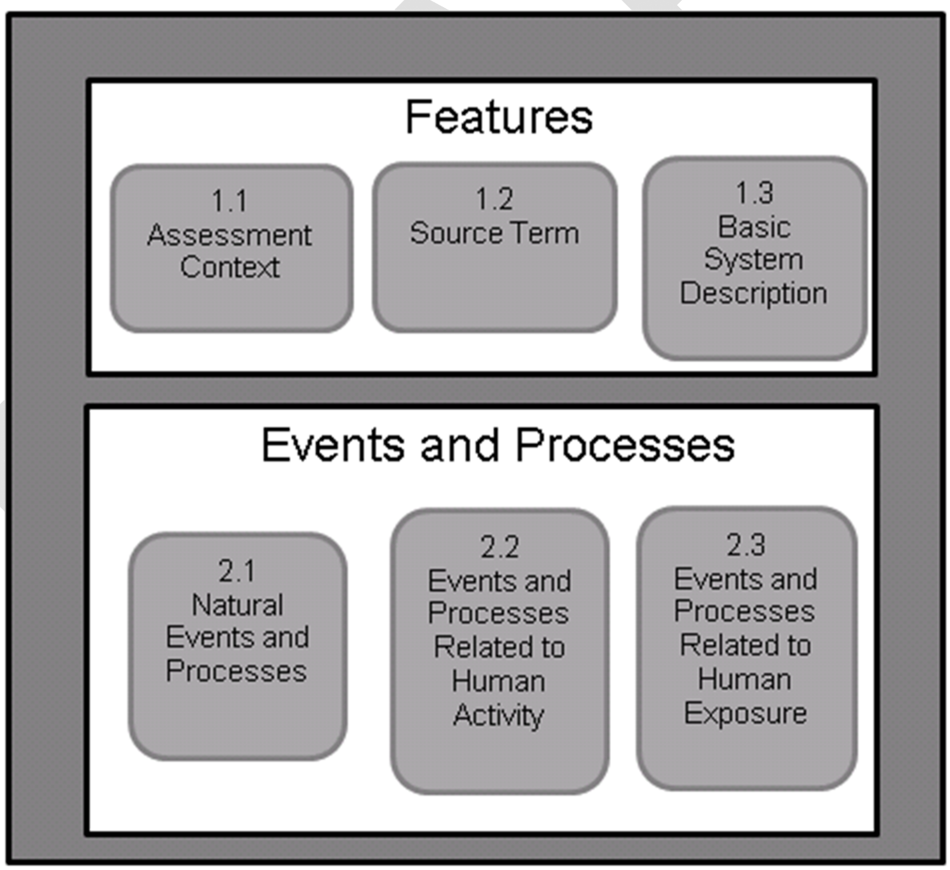

Figure C-1 Structure of BIOMOVs FEPs List

[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 is 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. The hierarchy of the ISAM FEPs list is similar to that of the NEA international FEPs list in Figure C-2[3].

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[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.

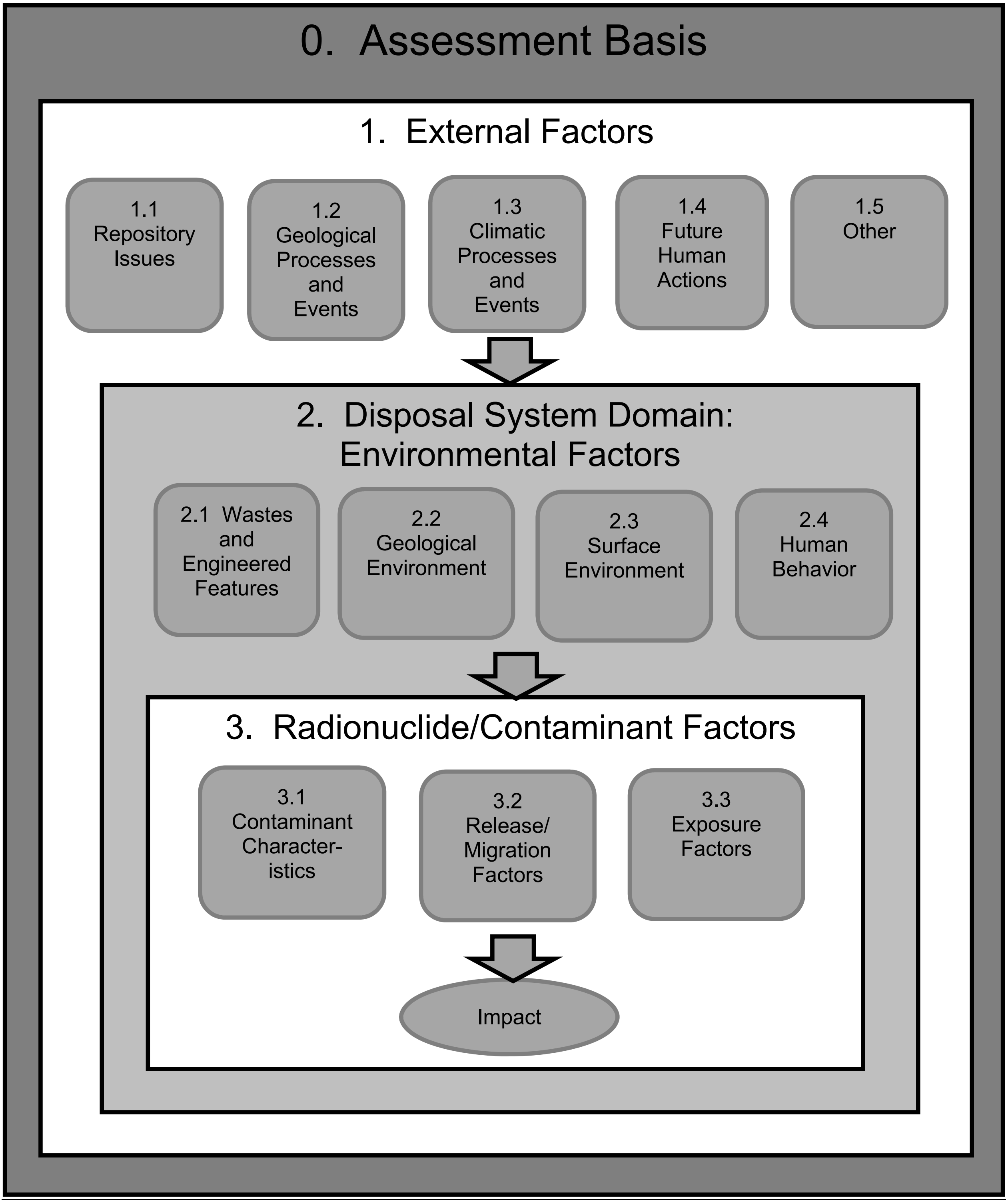

Figure C-2 Structure of the NEA FEPs list

BIOMASS

Changes were made to the organization of the BIOMOVS II list to develop the BIOMASS FEPs list. These changes included the following:

- providing 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
- expressing the intrinsic phenomena relating to the biosphere system in terms of characteristics of the system, rather than the behavior of radionuclides within the system
- incorporating experience gained with the application of the reference biosphere methodology since BIOMOVS II, which helped to amplify certain details of the original list and led to the incorporation of additional FEPs

Department of Energy (DOE) Hanford site

The Department of Energy has developed performance assessments to support the closure of underground storage tanks containing radioactive waste resulting from nuclear weapons production activities. 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) documented and examined 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 compilation of FEPs led to significant redundancy because some FEPs were included in numerous 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.

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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

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Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
43		Geological Intrusion
44		Hydraulic Fracturing
45		Intrusion 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 Ingrowth
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

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
84		Monitoring
85		Nuclear Testing
86		Operational Effects
87		Operational Error
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

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
126		Release of Stored Energy
127		Repository Seals
128	Exposure	Animal Ingestion
129		Dosimetry
130		Exposure Media
131		Human Behavior
132		Human Exposure
133		Ingestion Pathways
134		Inhalation Pathways
135		Agriculture

DOE Savannah River Site (SRS)

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. 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.

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 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.

[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.

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

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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

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

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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 LLW 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 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, and 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.

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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)

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
			Alternative Simplified Modeling Approach (SRS 1.3.13)
			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.

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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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			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/	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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hydrogeological response 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)

[20] Unnecessary speculation about future pollution should be avoided. Current and reasonably foreseeable pollution should be considered.

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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
Container materials, characteristics and degradation processes	2.1.03		Container materials, characteristics and degradation processes (e.g., corrosion) (HAN 2.1.03, CLV 96, CLV 97, CLV 100)
			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, mineraological 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 degradation (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)

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			Geophysical effects on degradation (CLV 36)
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)

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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			Episodic Or Pulse Flow and Release (SRS 5.1.03)
			Water Influx at the Closure Facility (SRS 5.1.04)
			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)

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			Long-Term Release of Radionuclides (SRS 5.3.14)
			Electrochemical effects (CLV 107)
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)

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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 geosphere) (e.g., fracture flow, porous flow, fracture/matrix interactions)	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)
			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)

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Chemical/geochemical processes and conditions (in geosphere)	2.2.08		Properties of the Groundwater Plume (BMO 1.2.3.2)
			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	2.2.12		Undetected features (in geosphere) (HAN 1.2.11, SRS 2.5.08)
			Breccia pipes (CLV 37)
			Lava tubes (CLV 47)

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pockets, geological features [faults, dykes, lava tubes, breccia pipes, lava tubes])			Gas intrusion (CLV 121)
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)

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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)
			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)

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
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)
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)

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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
			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)
			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 ingrowth	3.1.01		Radioactive decay and ingrowth (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)

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
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 and crystallisation, contaminant	3.2.01		Release Mechanisms (BMA 2,1.6.2, CLV 102)
			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)

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
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)
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)

[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
			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)
			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)

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
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)
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)
	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
Water management (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.

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APPENDIX D
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 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 subject matter 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 the significance of 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).

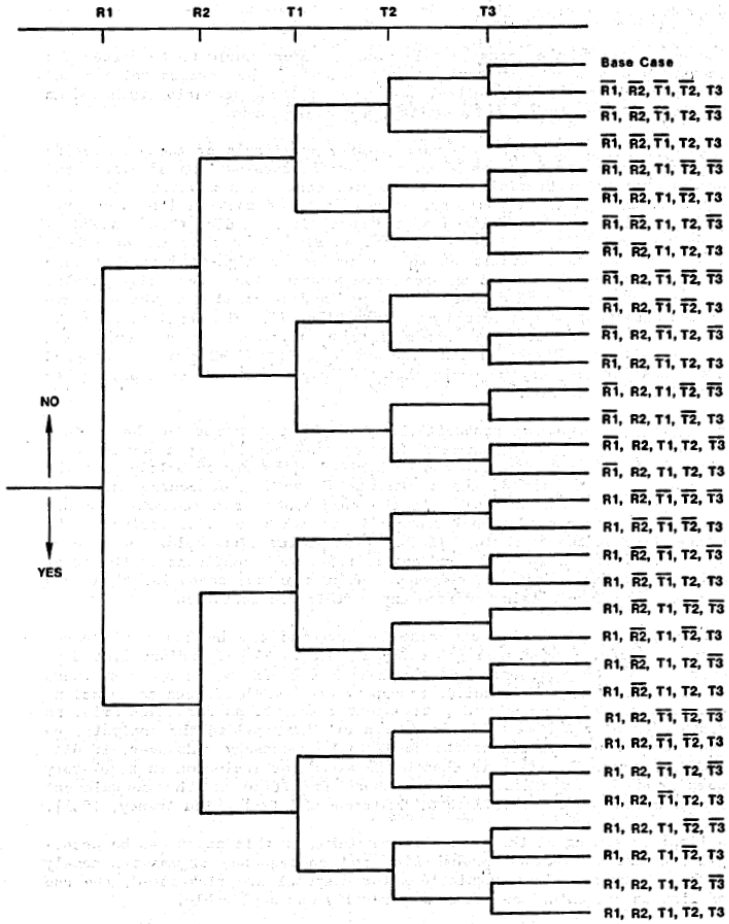

Figure D-1   Potential combinations of two release and three transport phenomena

In another example, alternative scenarios may be 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 is characterized by the continuation of current hydrologic conditions into the future. In Scenario 1, the probability of climate change, flood, and irrigated agriculture not occurring is 0.7, 0.8, and 0.4 (or 1-p), respectively, so that the probability of the scenario occurring is 0.7 x 0.8 x 0.4 or 0.224. For n events, this procedure will result in 2^n scenarios; some of these scenarios may be eliminated from further consideration because of insignificant probability or because the scenarios are not of regulatory concern. Since scenario development for LLW disposal is typically qualitative and exact probability values for events characterizing scenarios will usually not be available, qualitative science-based appraisals, such as large, medium, and small, would be 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.

		Events Characterizing Scenarios				
		Climate Change (p=0.3)	Flood (p=0.2)	Irrigated Agriculture (p=0.6)		
Scenarios	1	0	0	0	0.224	Scenario Probability
	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

Interaction matrices

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 irrelevant or 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."

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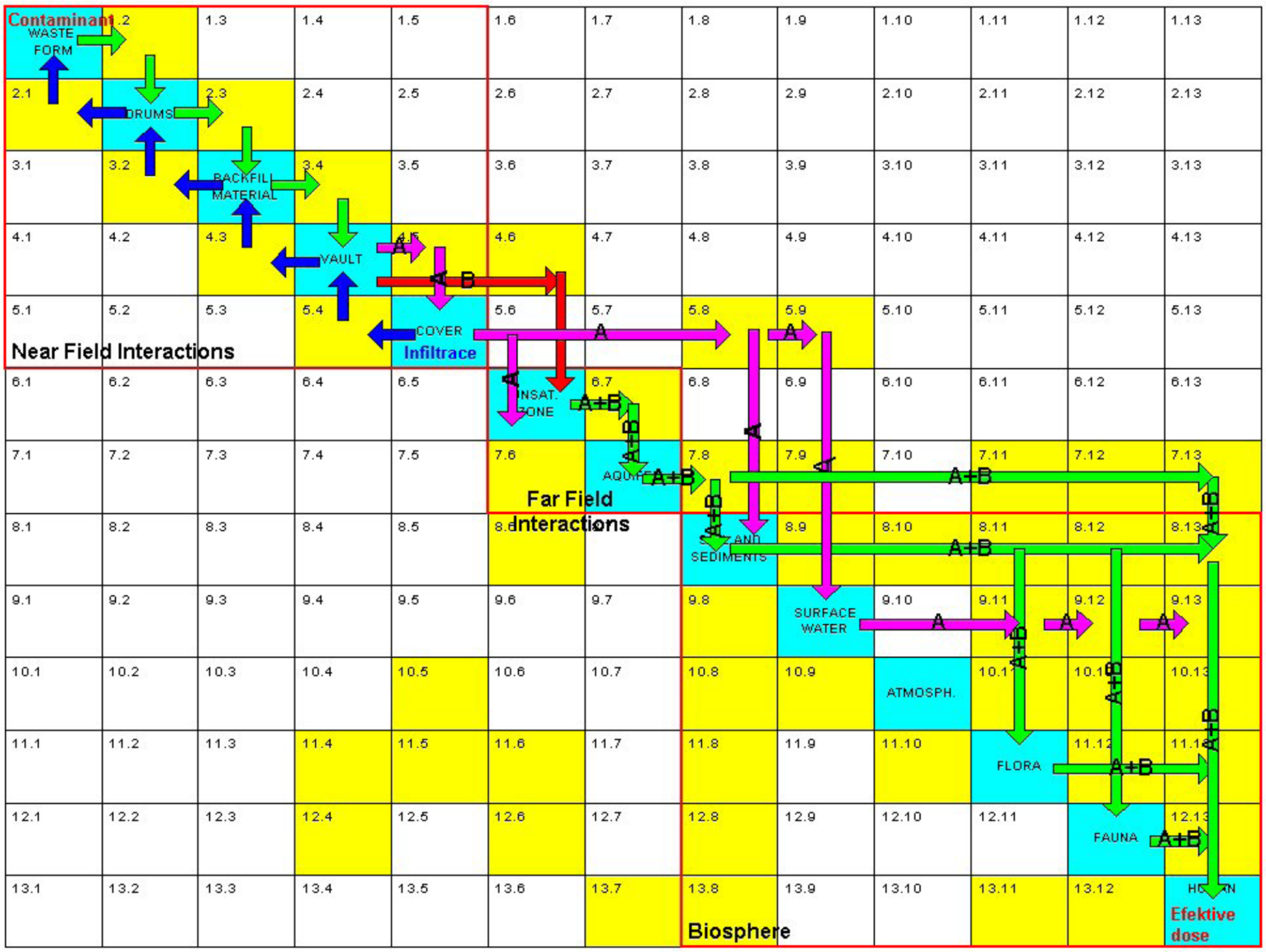

Figure D-3 Example of an interaction matrix for a central scenario including the bathtub effect (IAEA, 2004)

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 FEP 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 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).

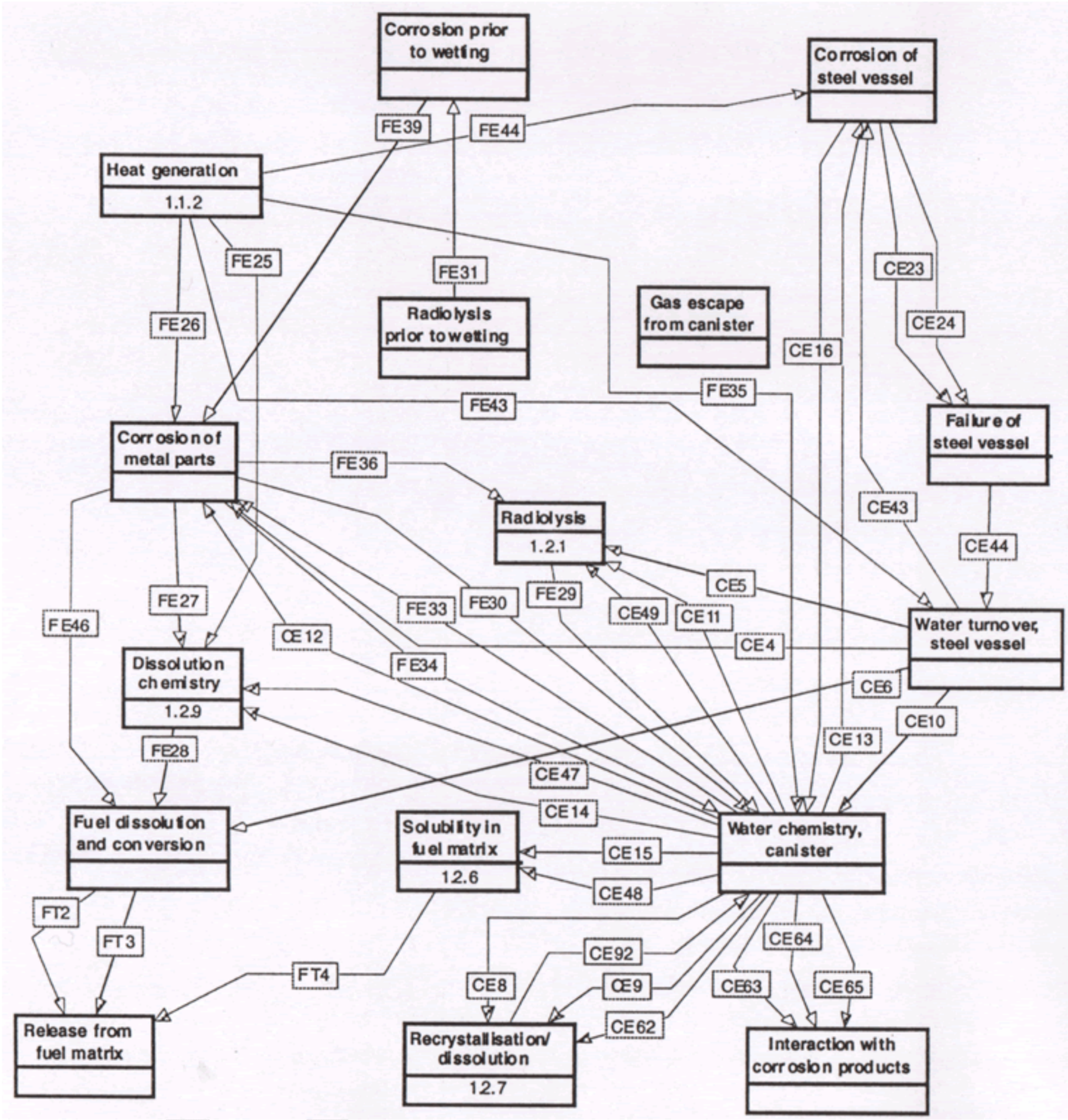

Figure D-4 **Example of an influence diagram for proposed repository PA in Sweden. Many of the specific phenomena reflected in this diagram are not expected be relevant to LLW (Chapman et al., 1995)**

The main steps to building the influence diagram can be summarized as follows (IAEA, 2004):

(1) 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.

(2) 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.

(3) 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.

(4) 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.

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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.

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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 Phased 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.

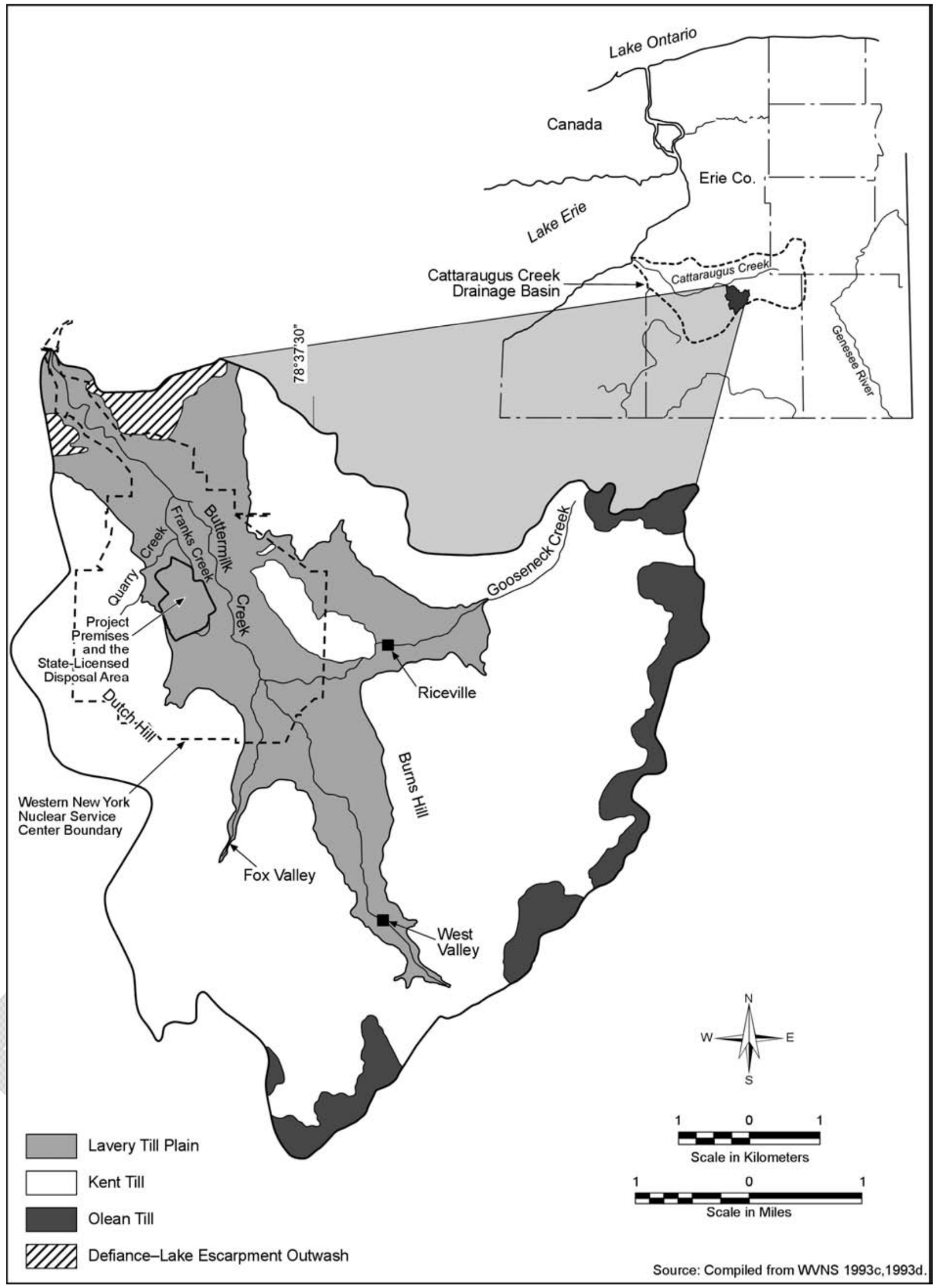

Figure E-1 Location of West Valley Site.
Image Credit: Figure F-2 (DOE, 2010)

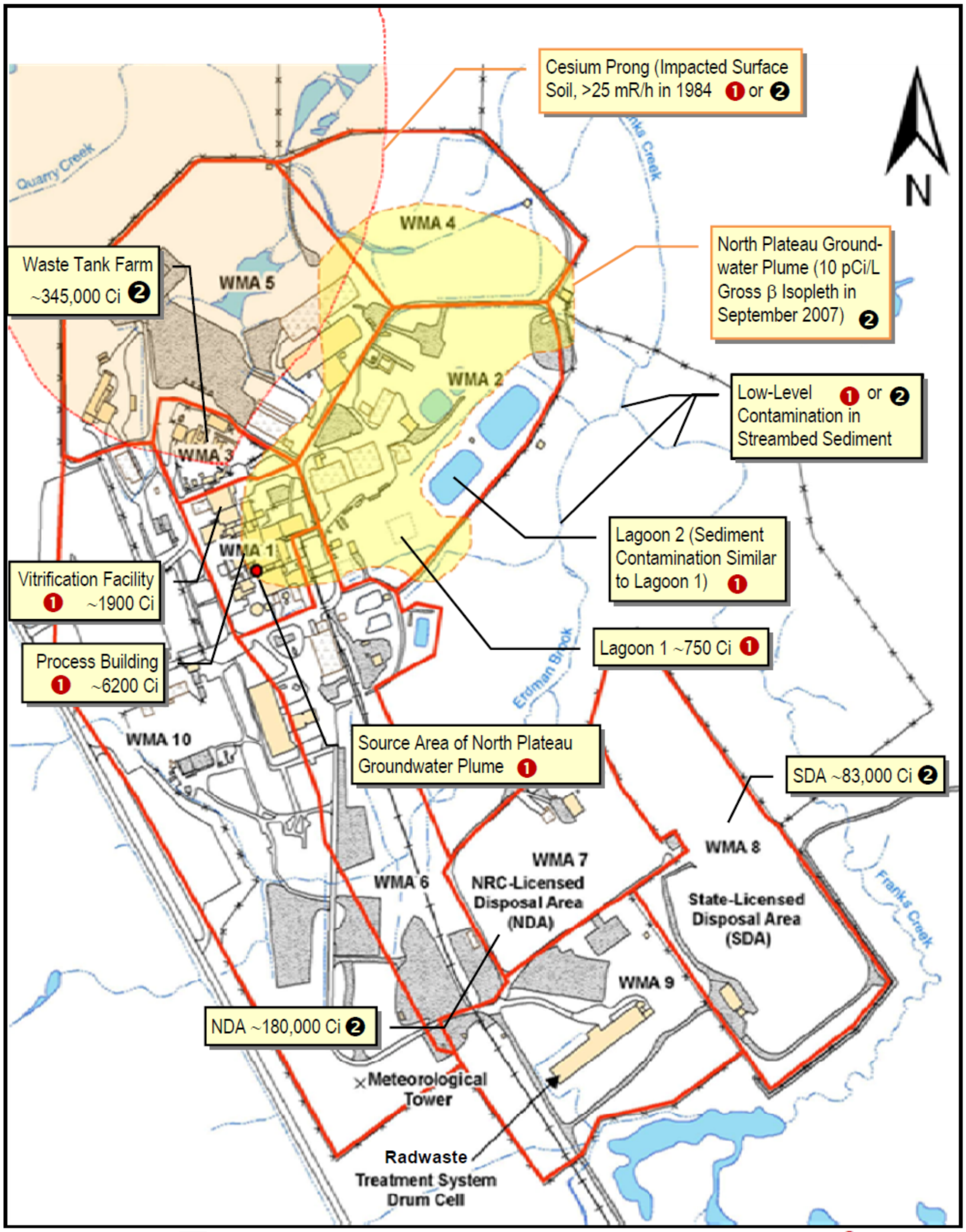

Figure E-2 Layout of West Valley Site and Source Areas to Be Addressed in Phase 1/2
Areas to be addressed in Phase 1 are marked with a ❶ symbol. Areas to be addressed in Phase 2 are marked with a ❷ symbol. Image Credit: Figure ES-5 (DOE, 2009)

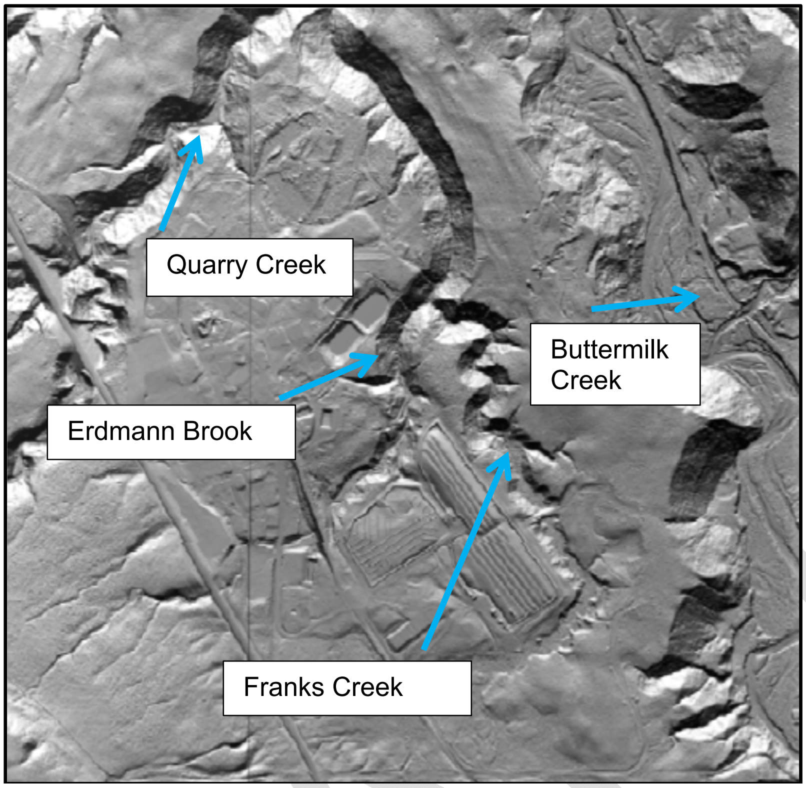

Figure E-3 West Valley Site Streams and Buttermilk Creek
Image Credit: Slide 3, Page 23, "Erosion Working Group Recommendations for Phase 1 Studies", August 22, 2012, Agenda/Presentation at http://westvalleyphaseonestudies.org/index.php/public-meeting.

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.

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Key Site Stability Technical Issue: Erosion

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).

West Valley CHILD Model

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.

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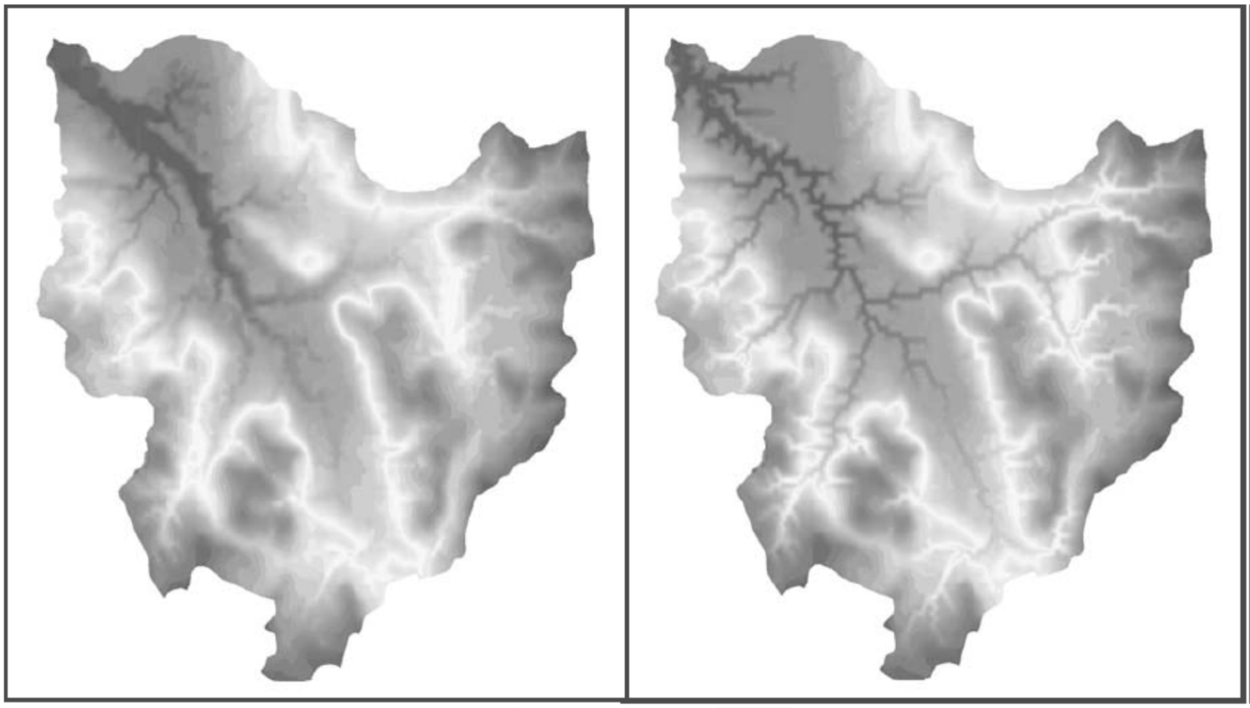

Figure E-6 Observed (left) and "Best-fit" (right) Model Run Topography
Image Credit: Figure F-8 (DOE, 2010)

<u>Potential Additional Data Collection Efforts</u>

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.

<u>Phase 1 studies may include the following (EWG, 2012b):</u>

1. *<u>Terrain Analysis</u>*

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.

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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. <u>Age Dating and Paleoclimate</u>

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. <u>Recent Erosion and Depositional Processes</u>

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

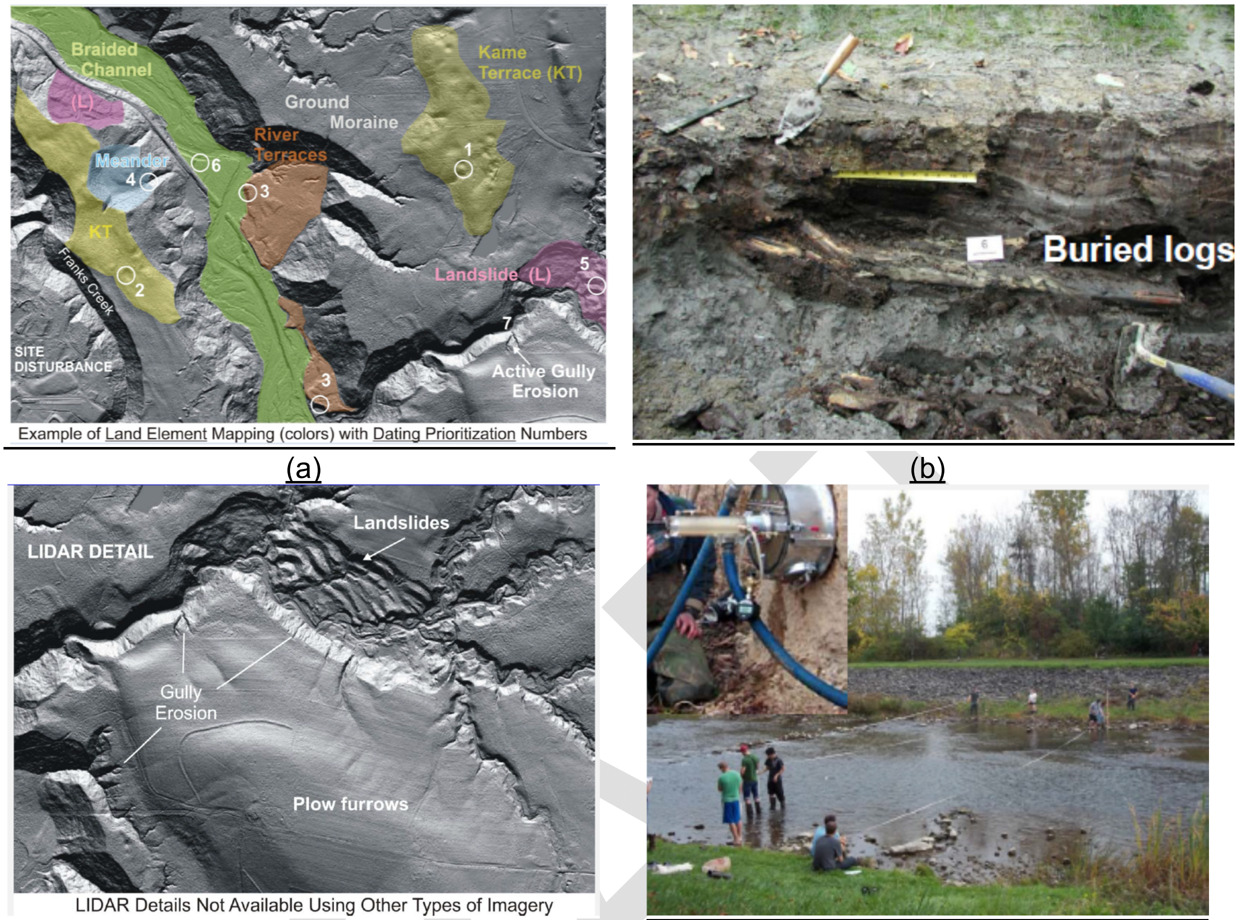
The purpose of the model refinement, validation and improved erosion prediction study would be to (i) improve confidence in erosion modeling predictions through independent validation, (ii) to reduce CHILD conceptual model and parameter uncertainty, and (iii) improve CHILD model calibration. All of these 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.



(a) (b) (c) (d)

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:

(1) Define model objectives.
(2) Develop or select the model.
(3) Document and provide the basis for assumptions.
(4) Parameterize the model.
(5) Calibrate the model.
(6) Verify the model.
(7) Characterize uncertainty.
(8) Provide model support.
(9) 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, either a model-based or design-based approach may be used to evaluate site stability. Typically, model-based approaches are used for longer periods of performance, while a design-based approach may be acceptable for shorter periods of performance. 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.

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Design-Based Approach: Moab UT Example:

Background

The Moab Mill was a uranium milling site that operated from 1956 until 1984 and contains mill tailings from uranium-ore processing. The Moab site is currently being remediated by United States Department of Energy under Title I of the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. Moab is located in Ground County, Utah, on the northwest shore of the Colorado River (see Figure E-8). The Uranium Reduction Company (URC) built and operated the Moab Mill beginning in October 1956. Atlas Corporation acquired URC in 1962 and operated the mill until 1984 when it was placed in stand-by status. Atlas submitted decommissioning and reclamation plans for the site, which were approved by the NRC in 1988 and 1999, respectively. In 1998, however, Atlas filed a petition for relief under Chapter 11 of the Bankruptcy Code. In October 2000, the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001 amended UMTRCA Title I, giving DOE responsibility for remediation of the Moab site. The NRC license was terminated, and the title to the site was transferred to the DOE in October 2001.

The remedial action plan proposed by DOE consists of removal and subsequent relocation of all residual radioactive material and contaminated materials from the Moab site to a disposal cell at Crescent Junction, Utah (also shown on Figure E-8). DOE proposes to construct an approximately 250-acre, engineered cell, partially below grade, to encapsulate the material. An engineered cover will limit radon migration from the cell, protect the cell from erosion, and reduce infiltration.

Moab Site Characteristics

The Crescent Junction Site is in the north end of the Canyon Lands section of the Colorado Plateau physiographic province. The Canyon Lands section is characterized by deeply incised drainages, isolated mesas, gently dipping bedrock, and anticlines formed by salt intrusion that have been breached in places by erosion to form anticlinal valleys. North of the Canyon Lands section is the Uinta Basin section of the Colorado Plateau; the boundary between the two sections is the Book Cliffs, an erosional escarpment just north of the site. The Uinta Basin section is characterized by a rugged, intricately dissected plateau bounded on the south by sets of cliffs (one of which is the Book Cliffs) that are highly irregular with many salients and canyons.

The Crescent Junction site is situated in the Mancos Shale Lowland at the foot of the book cliffs, a broad gently sloping area that is underlain by several thousand feet of Mancos Shale (see Figure E-9). The thickness of the Mancos Shale at the site is approximately 2400 feet based on a test hole drilled approximately 1750 feet south of the disposal cell location and on published geologic maps and literature of field and geologic mapping of the area. Ten coreholes were drilled to depths of approximately 300 ft into the Mancos Shale. Core samples were logged in the field using visual soil- and rock-classification procedures, and the coreholes were geophysically logged. DOE differentiates the Mancos Shale into “weathered” and “unweathered” portions. The primary difference between the weathered and unweathered Mancos Shale is the spacing of natural bedding plane fractures and high-angle fractures, both which decrease or are non-existent with depth in the unweathered Mancos Shale. This transition occurs at approximately 50 feet below the top of the Mancos bedrock surface.

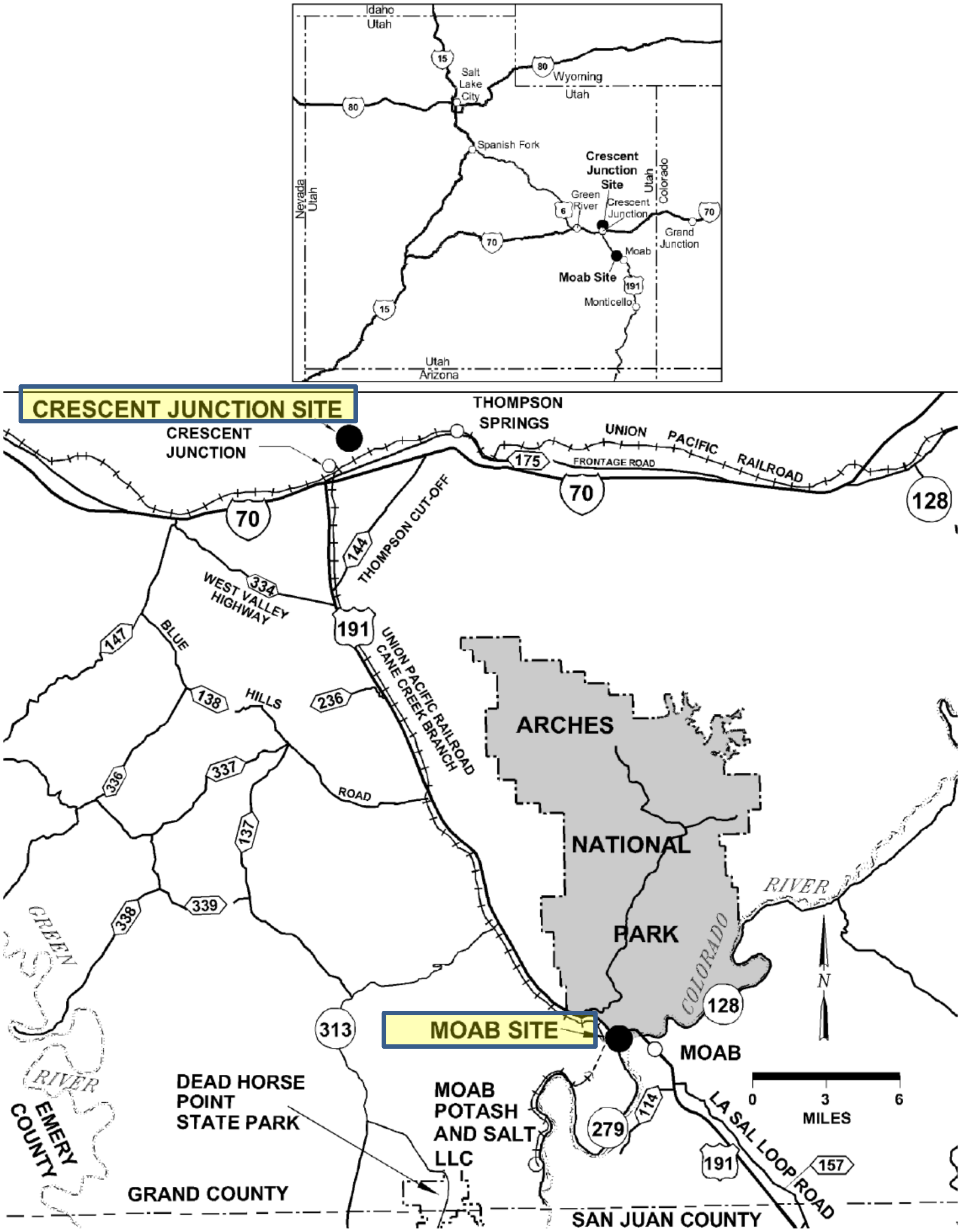

Figure E-8 Location of Moab and Crescent Junction Sites. Image Credit: Figure 1-1 (DOE, 2008).

Overlying the Mancos Shale is approximately 20-30 feet of alluvial and outwash material that has originated locally from the Book Cliffs. One hundred geotechnical boreholes were drilled to

depths as much as 26 feet through the surficial unconsolidated material into the shallow weathered Mancos Shale. Samples were logged in the field. Additionally, DOE dug five test pits ranging from 15 to 23 feet deep that assisted with the geologic characterization, and allowed hydraulic and geotechnical testing of the weathered Mancos Shale.

Underlying the Mancos Shale is the Dakota Sandstone containing the uppermost aquifer. The Dakota Sandstone is considered the uppermost aquifer because the Mancos Shale has an extremely high-saline content and poor quality and water quantity. Figure E-9 provides an illustration of the hydrostratigraphic system at Crescent Junction.

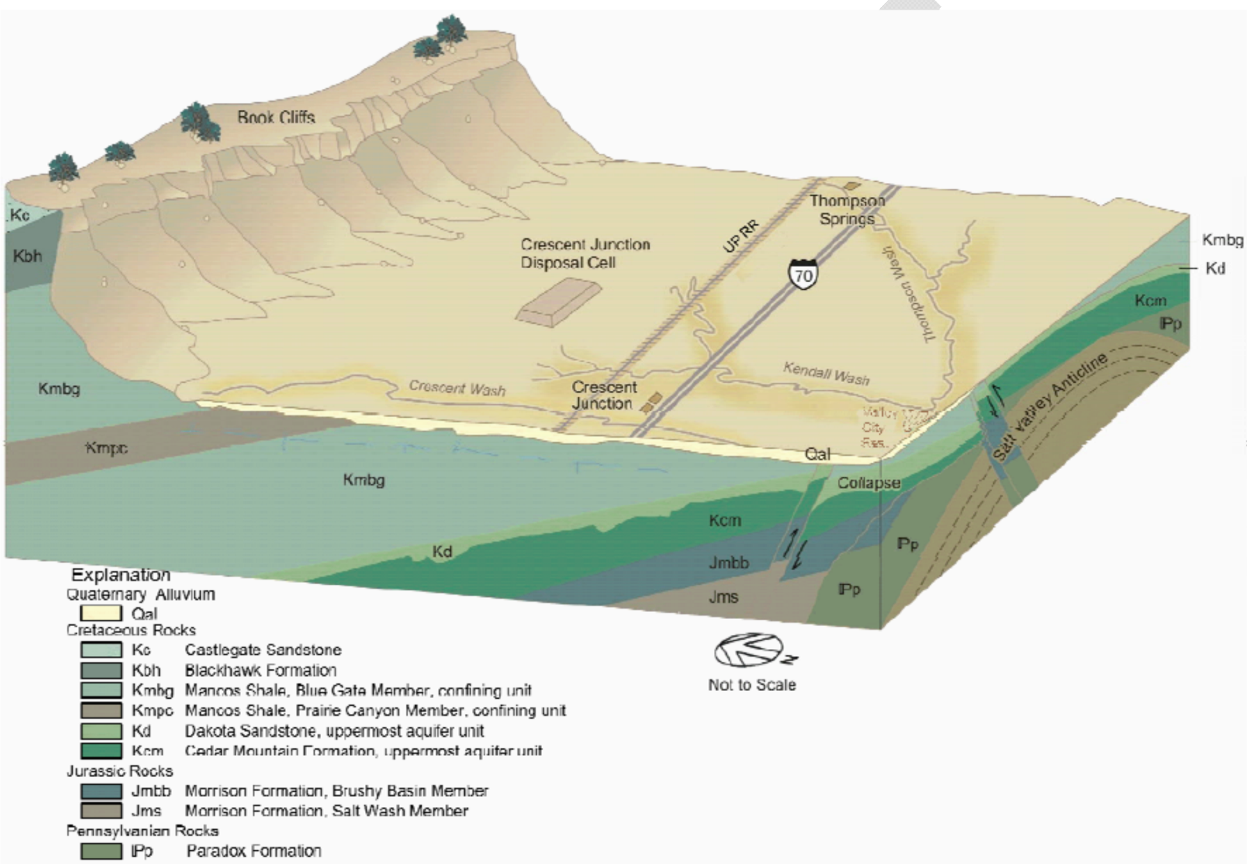

Figure E-9 Schematic of Hydrostratigraphic System and Topographic Features at the Crescent Junction Site. Image Credit: Figure 3-1 (DOE, 2008).

<u>Key Technical Review Area: Erosion Protection</u>

NRC staff reviewed DOE's Remedial Action Plan against the EPA requirements presented in 40 CFR Part 192, "Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings". To evaluate DOE's Remedial Action Plan, NRC staff used 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 elevations and velocities; sizing of riprap to be used for erosion protection; long-term durability of erosion protection components; and testing and inspection procedures to be implemented during construction. A description of DOE's design approach (DOE, 2008) and summary of NRC's review (NRC, 2008) is provided below.

Hydrologic Description and Erosion Protection Design

Regulations in 40 CFR 192 require stability of the tailings for 1000 years to the extent reasonably achievable and in any case for 200 years. In its Remedial Action Plan, DOE proposed to construct a disposal cell to protect the contaminated material from flooding and erosion. 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, were both considered as part of the design basis.

The top surface of the disposal cell was designed to drain in multiple directions at a slope of about two percent, and a 1 vertical on 5 horizontal (20 percent) slope was integrated into the design on the embankment side. Rock riprap would be used on the top and side slopes to protect against erosion. At the toes of the side slopes, rock riprap aprons would be constructed to provide protection against gully advancement toward the disposal cell. Several drainage channels would convey flood flows off the disposal cell and away from the disposal area. See Figure E-10 for an illustration of the dimensions, slope, and flow directions associated with the disposal cell.

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.

One of the phenomena most likely to affect long-term stability of the disposal site is surface water erosion. To ensure adequate protection against surface water erosion, the flood protection design should be based on conservatively selected events. DOE utilized a probable maximum precipitation (PMP) event as the design basis. The PMP was computed using deterministic rather than statistical methods, and was 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 assigned to the PMP; however, the probability of such an event being equaled or exceeded during the 1000-year stability period is very low. Accordingly, the PMP is generally considered by NRC staff to provide an acceptable design basis.

Hydrometeorological reports have been developed for specific regions that can be used to estimate the PMP. These techniques are widely used and provide straightforward procedures with minimal variability. PMP values were estimated by DOE using Hydrometeorological Report No. 49, or HMR-49 (NOAA, 1977). A 1-hour PMP of 8.2 inches was used by DOE as a basis for estimating PMFs for small areas at the site such as the top and side slopes. NRC staff concluded that the sources used to estimate PMP values and the PMP values themselves were acceptable in its Technical Evaluation Report (NRC, 2008).

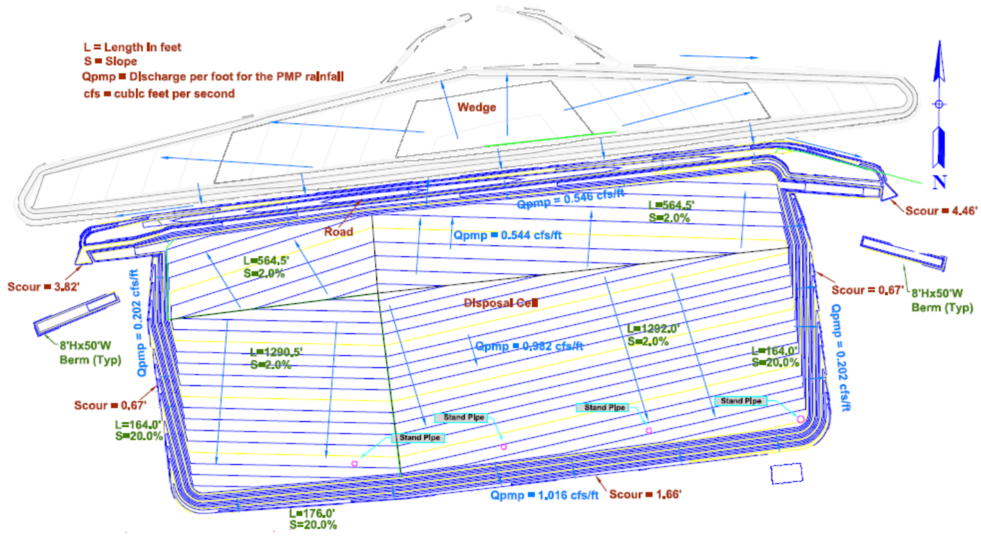

Figure E-10 Schematic of the Disposal Cell Dimensions, Slopes, Flows, and Scour Depths. Image Credit: Figure 6-3 (DOE, 2008).

The peak runoff rate is also dependent on the amount of precipitation that infiltrates into the ground during its occurrence, which is dependent on vegetation and soil type. 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, 1987) 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, 1998) 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 the conservatism of this parameter selection, the NRC staff concluded that the assumption was acceptable (NRC, 2008).

Another key parameter is the time of concentration (t_c), or 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. For example, 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. 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 were considered by the NRC staff to be appropriate for estimating times of concentration at the Moab site. Based on a review of the calculations provided, the NRC staff concluded that the t_c values used by DOE were acceptably derived (NRC, 2008).

NUREG-1623 (Johnson, 2002) recommends use of the Rational Method (Chow, 1959) for estimating flood discharges. In using the Rational Method to calculate PMF discharge rates for the top and side slopes, 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, NRC staff concluded that DOE's estimated flow rates were acceptable (NRC, 2008).

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}. 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. 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. 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 disposal cell, DOE proposed 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. DOE used methods suggested in NUREG-1623 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 planned to construct aprons along the toe of the side slopes. DOE planned to protect the area along the base of the south side slope by a rock toe/apron with a minimum D_{50} of 12 inches, while the toe of the north side slope would 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. DOE used the design criteria suggested in NUREG-1623 to determine rock sizes and rock volumes for the toe aprons. Based on staff review of DOE's analyses, the NRC staff concluded that the proposed rock sizes for the top slopes, side slopes, and aprons were adequate (NRC, 2008).

DOE proposed 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 concluded that the peak flows, rock sizes, and scour depths were acceptable (NRC, 2008). The diversion channels would extend several hundred feet past the edge of the disposal cell to prevent flows from directly impacting the cell side slopes. The channels would convey flows to the east and west sides of the cell and then would 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 would be provided to prevent gully headcutting into the spreaders. To reduce rock sizes to manageable levels, DOE intended to construct a pre-formed slope of 1 vertical on 10 horizontal (10 percent), and this slope will be extended to the expected scour depth. NRC staff review of the design of the riprap for the channel outlets indicated that the rock was large enough and extended to a sufficient depth to resist gully intrusion (NRC, 2008).

The north side of the disposal cell would normally receive runoff directly from the area between Book Cliffs and the cell. This area would be protected by constructing a barrier using a very large quantity of excess excavated material or “wedge”, which would act as a diversion berm to re-direct runoff away from the disposal cell. An access road between the cell and the wedge would be left in place. Runoff from the south side of the wedge would flow to the east and west in a ditch along the north side of the road, and runoff from the disposal cell would flow east and west along the south side of the road. Figure E-11 provides a cross-section through the wedge, ditches, access road, and north slope of the disposal cell.

The wedge would 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 would reduce the amount of sediment entering the diversion channels. DOE evaluated sediment accumulation in the ditches located adjacent to the access road and provided analyses to show that the riprap sizes are large enough to resist the increased velocities associated with a reduction in channel capacity.

Rock durability, or resistance to weathering, is a key factor in evaluating the long-term stability of the rock cover. For rock to remain effective to control erosion over the time periods relied on for performance, 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 NRC staff’s review conclusions are described below.

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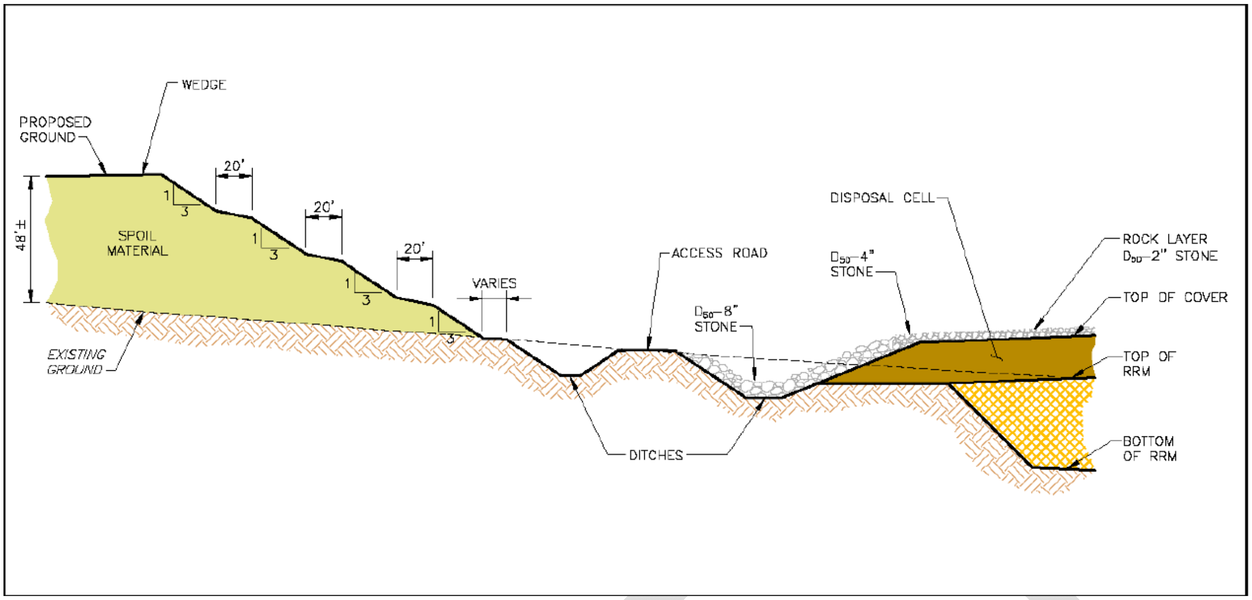

Figure E-11 Cross-Section Through Wedge, Ditches, Access Road, and North Slope of the Disposal Cell. Image Credit: Figure 6-7 (DOE, 2008).

A 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 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 (see Figure E-12 for picture of rock used at Green River site). 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.

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 relied on to support DOE's evaluation of rock durability for the Crescent Junction Site.

Figure E-12   Erosion Protection Cover at Green River Title I site

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 included 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 estimated that the volume of useable rock should be at least twice the volume required by the design of the erosion cover.

DOE estimated 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 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. DOE's rock production procedures indicated 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.

DOE evaluated rock durability using procedures outlined in NRC guidance found in NUREG-1623. The 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). Test data for both gray and red basalt samples from the Fremont Junction area were provided. These samples were collected in 1988 and 1989 for the Green River disposal cell; and in 2007 and 2008 for the Crescent Junction site. 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. DOE indicated that these samples were likely the vesicular red basalt. DOE's 1988-1989 quality control testing and scoring of four samples collected during the actual placement of the basalt cover at the Green River disposal cell resulted in additional scores for the Fremont Junction basalt that were higher than the initial test results. Scores for the Type A rip rap ranged from 78 to 90% with an average of 85%. Scores for the Type B rip rap ranged from 80 to 90% with an average of 83%.

DOE's scores from the 2007 and 2008 samples also 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 the DOE and NRC staffs to be more competent than the vesicular red basalt that had a low score (NRC, 2008).

DOE used information from field observations and the 1988 petrographic and x-ray diffraction analyses to identify if adverse heterogeneities or adverse minerals (e.g., olivine and clay) 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. DOE proposed to remove the overburden layer before excavation of the basalt alluvial deposit. DOE also proposed to screen out the finer matrix material from the basalt cobbles and bounders. 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.

DOE attempted to find evidence of resistance of the rock to weathering. This evidence 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 (e.g., weathering rinds). To confirm these observations and to resolve reports 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. 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 mentioned 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 support a determination

that the Fremont Junction basalt has remained resistant to weathering for thousands of years, well beyond the 1,000-year compliance period.

- Basalt boulders may have resisted weathering for 500,000 years based on the estimated age of the alluvial deposit, using a published stream 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.

The NRC staff concluded 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 (NRC, 2008). The NRC staff concluded that the Fremont Junction basalt is durable and should resist weathering and associated size reduction for at least the 1,000-year compliance period. Therefore, the NRC staff considered the Fremont Junction basalt acceptable for use in the erosion controls at the Crescent Junction site.

DOE also provided information regarding testing, inspection, and quality control procedures to be used for the erosion protection materials. Because there was indications that the rock in the proposed quarry could be somewhat variable in certain locations, DOE provided information to document the quality assurance and quality control (QA/QC) procedures that would be implemented during rock production to address this variability and to assure that rock of acceptable quality would be consistently produced.

DOE plans included stripping overburden from the alluvial deposits and separation of this material from the basalt cobbles and boulders. Rock materials would be excavated, crushed, and screened into stockpiles of various sizes. The rock would then be crushed and further screened, as necessary, to produce the required rock sizes. These primary and secondary sorting processes should assure that rock would be relatively homogeneous and that visible portions of the stockpiles would be representative of the entire stockpile. Crushing and screening would 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. Based on observations during a June

2008 site visit and information provided by DOE, the NRC staff concluded that the proposed program for rock production was acceptable (NRC, 2008).

DOE proposed that rock durability and gradation testing would be performed a minimum of four times and/or at a frequency of one test for every 10,000 cubic yards of material produced as recommended in NUREG-1623. Rock durability testing would include the following:

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 review of the information submitted by DOE and independent NRC staff calculations, the NRC staff concluded it had reasonable assurance that the erosion protection requirements in 40 CFR 192 would be met (NRC, 2008).

<u>How Does the Moab Design-Based Example Relate to 10 CFR Part 61 Guidance?</u>

The Moab example illustrates the design-based approach described in Section 5.2.2 of this document and reproduced below for ease of reference. This approach may be used to assess performance of a 10 CFR Part 61 facility.

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 (technical basis) for the design.
vii. Iterate, if necessary.

DOE clearly defined design objectives for the erosion protection system at the Crescent Junction site. DOE provided sufficient detail on the selected design, as well as sufficient information to support its calculations and assessments. Supporting information included information from the literature, field observations, testing, and analog studies. In demonstrating compliance with the applicable regulatory criteria, DOE followed guidance provided in NUREG-1623, which provides acceptable methods for designing erosion protection systems to help ensure site stability at NRC regulated facilities, greatly facilitating the NRC staff's review.

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APPENDIX F
RESPONSE TO COMMENTS RECEIVED ON DRAFT NUREG-2175

F.1 Energy Solutions

July 24, 2015, ADAMS Accession No. ML15215A291
April 20, 2016, ADAMS Accession No. ML16117A209 and ML16117A210

<u>Chapter 1: Introduction</u>

F1.1.Summary (S1) *Comment*: The document introduces designations for individual technical analyses that are not cited in the proposed rule and inconsistently refers to these analyses in multiple chapters. This lack of consistent language throughout the documents would create an opportunity for the user community to misinterpret or possibly misapply the Commission's intent when developing the safety case. (Also **F1.1.2, F1.1.6**) In Section 1.1, the titles and definitions should match the terminology in the proposed rule.

Response: The definitions for the technical analyses discussed in NUREG-2175 have been revised and made consistent with the definitions in the final rule at §61.2 and §61.13. Specifically, the technical analyses include the performance assessment, inadvertent intruder assessment, site stability analyses, and performance period analyses. The requirement for defense-in-depth analyses and protective assurance period analyses have been removed from the list of technical analyses required to demonstrate meeting performance objectives. Instead, defense-in-depth discussions in NUREG-2175 have been made consistent with the final rule at §61.7(d).

Changes were made to the guidance as a result of this comment.

F1.1.1 *Comment:* Section 1.0; the document would be improved by providing detailed guidance on how to prepare a technically defensible safety case and this would be best stated in Chapter 1. (Also **F3.1**)

Response: Section 1.1.2 of NUREG-2175 summarizes the safety case and what it entails, as required by 10 CFR Part 61. The safety case, consistent with 10 CFR 61.2, is the collection of information that demonstrates the assessment of the safety of a land disposal facility. As required in 10 CFR 61.10, the content of a safety case includes the information provided in an application that supports the licensee’s demonstration that the land disposal facility will be constructed and operated safely and provides reasonable assurance that the disposal site will be capable of isolating waste and limiting releases to the environment. These include general and technical information required by 10 CFR 61.11 and 61.12, the technical analyses required in 10 CFR 61.13, and institutional, financial, and other information required in 10 CFR 61.14 through 61.16. The NRC staff provides detailed guidance on the contents of an application in NUREG-1200 (NRC, 1994). The guidance in NUREG-1200 is supplemented by detailed guidance on conducting the technical analyses in NUREG-1573 and as updated in Sections 2.0 through 6.0 of this document. Sections 7.0 through 8.0 of this document provide guidance on identifying defense-in-depth protections and describing their capabilities and developing waste acceptance criteria. The NRC staff has revised Section 1.1.2 of this document to more clearly

reflect the expectations for the safety case embodied in the regulations and the detailed guidance that currently exists to develop the safety case.

Changes were made to the guidance as a result of this comment.

F1.1.2 See Comment Response F1.1.S1. This comment was similar in content to F1.1.S1, so the comments were binned together.

F1.1.3 *Comment:* Section 1.1.2; because the WAC is relied upon to ensure that the performance objectives are met, the WAC should be included as part of the safety case.

Response: The NRC staff agrees that the waste acceptance criteria are an important component of the safety case and has included waste acceptance criteria as part of the safety case as required in 61.12(i). The NRC staff has revised Section 1.1.2 of this document to more clearly identify that the contents of a safety case, consistent with 10 CFR 61.10 and 61.12(i), include the waste acceptance criteria.

Changes were made to the guidance as a result of this comment.

F1.1.4 *Comment:* Section 1.1.2; updating the safety case as part of the application for site closure is unwarranted and unnecessarily burdensome for licensees with sites having conditions that have been determined to adhere to the existing safety case. The section should be modified to discuss circumstances which an update is required, and to make an allowance for facilities with no changes to retain the existing safety case.

Response: According to the requirements of §61.28(a), licensees are required to submit a final revision to the safety case, which is required in §61.10, and to provide updated technical analyses and defense-in-depth identifications using the details of the site closure plan and LLW inventory. Under §61.28(c), the NRC can only authorize closure of the LLW land disposal facility if there is reasonable assurance that the long-term performance objectives of Subpart C will be met. For licensees who have adhered to an existing authorized safety case, revisions to the safety case may be minimal and should reflect new information that could significantly impact safety of the facility (e.g., final inventories disposed or any changes necessary for safe closure of the land disposal facility). The NRC staff has revised the guidance in Section 1.1.2 of this document to clarify that changes to the safety case are dependent upon the licensee's operation and closure of the land disposal facility.

Changes were made to the guidance as a result of this comment.

F1.1.5 *Comment:* Section 1.1.3; the placement of this subsection implies that defense-in-depth is a separate analysis, yet the text itself re-iterates our position that the concept of defense-in-depth should be incorporated into the other technical analyses and is not an independent analysis. This section should focus more on how the Commission would like the defense-in-depth protections highlighted throughout the other technical analyses.

Response: All the technical analyses are discussed in Section 1.1.4, therefore, the placement of defense-in-depth in Section 1.1.3 was intended to suggest that defense-in-depth is not a separate technical analysis. Nevertheless, Section 1.1.3 was updated to clarify that the licensee must identify defense-in-depth protections for their facility and may use the results of the technical analyses listed in Section 1.1.4 to describe their capabilities but that no separate analysis was required.

Changes were made to the guidance as a result of this comment.

F1.1.6 See Comment Response F1.1.S1. This comment was similar in content to F1.1.S1, so the comments were binned together.

F1.1.7 *Comment:* Section 1.1.4; to align with our comment that the rule should only contain definitions of the analyses and the discussion around the analyses should be relocated to the guidance, we suggest that much of the language in §61.13 of the proposed rule be removed and relocated to this section, which provides explanations of the technical analyses required.

Response: The NRC agrees with some of these concerns. The proposed regulation provided 10 requirements for the performance assessment in §61.13(a). Some of the requirements have been deleted from the final rule while others have been retained. The requirements that were deleted from the rule were moved to this NUREG-2175, as appropriate.

For example, the proposed §61.13(a)(9) was deleted from the rule because it was deemed to be duplicative with the proposed §61.13(a)(6). Model support is critical to performance assessments (§61.13(a)(6)). Consideration of alternative conceptual models of features and processes is an important technique to address the inevitable situation for complex waste disposal problems where model uncertainty cannot be effectively reduced (§61.13(a)(9)). However, additional information about alternative conceptual models of features and processes is provided in NUREG-2175.

The NRC also agrees that a separate requirement, as proposed in §61.13(a)(5), regarding degradation or alteration processes, was unnecessary. The proposed §61.13(a)(5) was deleted because it was deemed to be duplicative with §§61.13(a)(1) and 61.13(a)(3). Further discussion of degradation or alteration processes is now discussed in NUREG-2175. The requirements for consideration of FEPs have been simplified and the separate requirement for consideration of degradation or alteration processes has been deleted. The requirement in the proposed §61.13(a)(10) plays an important role related to understanding the significance of the major components of the disposal system in mitigating or reducing risk. This information is valuable in risk-informing the review of disposal system performance. Therefore, the paragraph has been retained as §61.13(a)(6) in the final rule. Consideration of FEPs and description of how the integrated system of FEPs is functioning are two different concepts.

Changes were made to the guidance as a result of this comment.

F1.1.8 *Comment:* Section 1.1.4.2; the background regarding the basis for an inadvertent intrusion is helpful by citing the corresponding technical basis for the analyses. We recommend a similar basis for each analysis referenced in this section.

Response: Additional background and/or technical basis was added in Section 1.1.4.

Changes were made to the guidance as a result of this comment.

Chapter 2: General Technical Analysis Considerations

F1.2.S1 *Comment:* The requirements outlined in this chapter are overly burdensome, and the staff did not adequately assess the time and effort for licensees to complete the technical

analyses. Staff should reassess the requirements for technical evaluations, eliminating overly burdensome suggestions, such that the anticipated level of effort and costs associated with the technical analyses are more appropriately aligned with the associated risk. The requirements for model validation, data adequacy review, and uncertainty quantification should be significantly reduced or eliminated.

Response: NUREG-2175 does not provide requirements; it supplies methods or approaches a that the NRC staff would find acceptable to assist a licensee in demonstrating a site's ability to meet the regulatory requirements provided in the rule.

Section 2.1.2 in NUREG-2175 specifically discusses the level of effort deemed prudent for various tasks within the performance assessment effort. 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), should be commensurate to the longevity, concentrations of radionuclides, quantity of the waste, and the degree of geologic and geomorphic stability of the site. 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 depleted uranium. In addition, any disposal site that has a high degree of geologic and geomorphic stability would require considerably less time and effort to assess than other sites with many dynamic processes. For example, due to the many potential disruptive processes that would need to be incorporated into the performance assessment process, a designated disposal site on the Big Island in Hawaii would most likely require considerable effort to demonstrate that the performance objectives would be met in comparison to a designated site in one of the southern Great Plains states. Time and effort spent on scenario development for those sites with geologically stable characteristics and intended for relatively short-lived radionuclides disposal should not be excessive and the process is relatively straightforward. Appendix C in NUREG-2175 provides several generic FEPs lists for potential sites being considered for near-surface disposal of LLW.

Model validation is only briefly discussed in NUREG-2175 in the discussion about model support or when confirming the difficulty or impossibility of validating model simulation results for time periods extending relatively far out into the future. "Providing assurance of results," as stated in the comment, is not possible for long-term simulation results; however, the results for the performance assessment process should allow the decision-makers to obtain important information and insights to lend more confidence when making required decisions. The guidance on data adequacy is less than one page and discusses the sufficiency of data and the appropriateness of use. In addition, uncertainty quantification as defined in the traditional sense is only briefly discussed in Section 2.0. It should be noted that a later comment recommends NRC staff draft a subsection to specifically address how to perform an uncertainty quantification analysis. A response for that comment can be found under comment response F1.2.S4.

No changes were made to the guidance as a result of this comment.

F1.2.S2 *Comment:* The content regarding the considerations of FEPs, scenarios, model development presented in this chapter are too prescriptive, unnecessarily conservative, and in some instances circular. The level of detail describing how to perform the technical analyses should be reduced, such that the chapter describes a clear path for performing technical analyses that allows licensees flexibility in the overall approaches used to demonstrate compliance objectives are met.

Response: NUREG-2175 does not provide requirements; it supplies methods or approaches that the NRC staff would find acceptable to assist a licensee in demonstrating a site's ability to meet the regulatory requirements provided in the rule.

The level of effort necessary for the performance assessment process should be commensurate with the risk to the public from the disposal of the waste. Specifically, the level of effort should be commensurate to the longevity, concentrations of radionuclides, quantity of the waste, and the degree of geologic and geomorphic stability of the site, and therefore, should not be unnecessarily conservative. Although, the performance assessment process is usually an iterative process, it should not be a never-ending analysis. New knowledge and information is usually gathered as the project and associated technical analyses move forward, and the analyst may need to step back and reconsider some of the previous steps performed. For example, it may happen that while developing an alternative conceptual model or constructing the numerical model, it becomes clear that certain components of the system are more significant that previously assumed and features and processes related to the components need to be reanalyzed. Waste with short-lived radionuclides and sites with geologic and geomorphic stability may have minimal or no iterative processes, while long-lived wastes and complex sites may be associated with more uncertainty, and subsequent discoveries and insights may require certain steps from the performance assessment process to be reevaluated.

No changes were made to the guidance as a result of this comment.

F1.2.S3 *Comment:* Time periods for analyses and additional considerations for the assessment of site characteristics based on waste concentration are introduced in chapter 2, including for example in Section 2.3.2.4. These time periods are not included in the rule and introduce confusion. It is not clear how these timeframes for analyses based on concentration limits should be incorporated into other analyses including site stability, intruder analysis and protective assurance period compliance analyses. We request the guidance be revised to ensure consistency throughout the rule and guidance documents. Analysis requirements should not be in the guidance that are not included in the rule. (Also **F1.2.10)**

Response: NUREG-2175 does not provide requirements; it supplies methods or approaches that the NRC staff would find acceptable to assist a licensee in demonstrating a site's ability to meet the regulatory requirements provided in the rule.

The approach to timeframes has been revised for the final rule, therefore, the material in Section 2.3.2.4 has been revised to maintain consistency. Section 2.3.2.3 (formerly 2.3.2.4) provides an approach that the NRC staff would find acceptable to use for considering site characteristics. The language in §61.7(a)(2) states that in choosing a disposal site, site characteristics should be considered in terms of the indefinite future, take into account the radiological characteristics of the waste, and be evaluated for at least a 500-year timeframe to provide assurance that the performance objectives can be met. The guidance in Section 2.3.2.3 provides an interpretation of the "indefinite future" language that the NRC staff finds acceptable for the consideration of site characteristics, by providing example calculations that can be performed to determine the timeframes to evaluate site characteristics based on the site-specific projected facility volume (or mass) and the concentrations provided in Table 2-2 (added in the final NUREG). No new timeframes are introduced in this section.

Changes were made to the guidance as a result of this comment.

F1.2.S4 *Comment:* Accounting for uncertainty is a theme that is addressed numerous times throughout this chapter in separate subsections. In many cases, the discussions and examples for addressing uncertainty are incomplete. Instead of weaving comments and requirements around uncertainty through the text, we recommend the Staff draft a subsection to specifically address how to perform an uncertainty quantification analysis.

Response: There are many types of uncertainties associated with performance assessments that evaluate the performance of proposed disposal facilities for long-lived wastes. Such uncertainties include the unknowns connected with the future evolution of the site, uncertainty in the conceptualization of the system, uncertainty in the actual numerical model itself, and uncertainty about the adequacy and quality of the data.

The NRC staff attempted to find the appropriate balance between overall completeness of the methodologies for conducting technical analyses for 10 CFR Part 61 and providing too much detail as to make the document lose focus and become unwieldy and difficult to use. For the treatment of data uncertainty, uncertainty techniques by which uncertainty in model parameters is propagated through the model are comparatively well-documented and widely published so that analysts or statisticians have relatively easy access to various techniques such as statistical sensitivity analysis based on Monte Carlo sampling, regression methods, or distribution partitioning intercept methods. However, the NRC staff agrees that a subsection is needed to briefly discuss such techniques and how they fit in to the overall uncertainty analysis. A new Section 2.7.4.1 was added that discusses parametric uncertainty and sensitivity analyses and how they complement those analyses that assess uncertainty associated with future site evolution and plausible alternative conceptual models.

Changes were made to the guidance as a result of this comment.

F1.2.1 *Comment:* Section 2.1; the discussion around accounting for uncertainty is overly simplistic and incomplete. Model uncertainty cannot be accounted for simply by developing and analyzing conceptual models. The guidance should include a more thorough discussion on uncertainty quantification and propagation.

Response: As stated in Section 2.2.3.1.2, 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. However, the NRC staff also discusses scenario and data uncertainties, which includes evaluating uncertainty associated with the parameters and parameter ranges. The commenter stated that the assessment process relies upon multiple models with some model outputs being inputs of other models, and that uncertainty quantification becomes a computationally expensive and time consuming exercise. However, depending on the assessment context, performance assessments do not necessarily need to rely on multiple models. The NRC staff have produced and evaluated performance assessments composed of a single model.

A Section 2.7.4.1 has been added to discuss parametric uncertainty and sensitivity techniques and how they fit into the overall uncertainty analysis.

Changes were made to the guidance as a result of this comment.

F1.2.2 *Comment:* Section 2.2.1; parameter uncertainty is described in §2.2.2.1.3, not §2.2.2.1.2 as referenced in the text.

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Response: This error has been corrected in the current section 2.2.3.1.3 of final NUREG-2175.

F1.2.3 *Comment:* Section 2.2.2; the italicized emphasis on scenario uncertainty when describing uncertainties in the performance assessment is confusing and might lead the licensee and/or reviewer to place a greater emphasis on scenario uncertainty. We recommend staff provide better support for the emphasis or eliminate the use of italics.

Response: Terms in the glossary are italicized at first use.

F1.2.4 *Comment:* Section 2.2.2; Figure 2.2 is oversimplified and does not provide an adequate representation of uncertainty analysis and the treatment of uncertainty. The figure seems to imply that the same parameter sets might be used in all models, potentially modeled using the same distributions and or discretization, and that all parameter sets will be incorporated into making a decision, which might not be appropriate. Additionally, the figure does not depict model interaction and parameter interaction, and the use of submodels interwoven together to ultimately predict radiation release. Recommend the figure be updated to reflect the true level of effort required to account for future, model, and parameter uncertainty, or the figure should be removed the text.

Response: Figure 2-2 is taken from NUREG/CR-5927, Vol. 1 and correctly represents a general structure of uncertainty analysis that treats uncertainty associated with models, data, and future evolution of the site. Although the parameter sets for each conceptual model are not uniquely labeled, i.e., each begins with set number 1 and continues from there. The authors of NUREG/CR-5927, Vol. 1 may have decided not to label each parameter set uniquely since it is possible that some parameter sets may be the same for different conceptual models. Aside from the intent of the authors, the figure does not imply that the same parameter sets should be used in all models since this would result in all plausible conceptual models being identical. However, each parameter set could provide decision makers some insights into the disposal system under consideration. As for the use of many models or submodels to complete a performance assessment that can be, but is not necessarily, true.

No changes were made to the guidance as a result of this comment.

F1.2.5 *Comment:* Section 2.2.2.1.2; the requirement that when data are sparse, multiple conceptual models should be evaluated and the most conservative model selected is overly burdensome. It is difficult to assess which model is actually the most conservative for the data considered without actually constructing and running the model. This requirement should be eliminated.

Response: NUREG-2175 does not provide requirements; it supplies methods or approaches that the NRC staff would find acceptable to assist a licensee in demonstrating a site's ability to meet the regulatory requirements provided in the rule.

The task confronting a potential licensee of a disposal site that has sparse data will usually be considerably more difficult to perform than a licensee that has abundant data. Analysts with abundant data could use that information to exclude alternative conceptual models while the analysts with little data may need to assess the different conceptual models, since it may not be possible to exclude them due to the lack of information.

No changes were made to the guidance as a result of this comment.

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F1.2.6 *Comment:* Section 2.2.3; we agree with the NRC that the technical analyses required by the performance assessments and site stability analyses cannot be validated in the traditional sense, and that the greatest sources of uncertainties in the performance assessment are due to projecting out models calibrated with relatively brief histories across periods of time that are orders of magnitude greater than the calibration periods. Given the level of effort required to perform the technical analyses, including the iterative process of parameter characterization, model calibration and model verification, we question the validity and benefit of performing quantitative analyses beyond 1,000 years.

Response: The NRC staff disagrees that the long-term analyses results are invalid because they cannot be validated in the traditional sense, and also disagrees that there is no benefit to performing quantitative analyses beyond 1,000 years. As outlined in former Section 2.2.4 (former Section 2.2.3), model support is one of the most essential technical elements associated with demonstrating compliance with the performance objectives. The section outlines the types of information that can be used for model support and that model support can be commensurate with the significance of the system/subsystem to achieving protection.

The commenter did not provide basis as to why they believe quantitative analyses results are considered to be invalid beyond 1,000 years but are valid before this timeframe. Iterative model development, model calibration, and verification are necessary for any compliance period (greater or less than 1,000 years). Quantitative technical analyses results beyond 1,000 years have been successfully used to ensure the safe disposal of low-level waste in the United States and throughout the world for over 25 years. The benefit of the technical analyses results is to supply information for a license to demonstrate the safety of the waste disposal action. It is not clear what information would be used to ensure protection of public health and safety from the near-surface disposal of significant quantities of long-lived radionuclides without technical analysis. In the final regulation, the compliance period is 1,000 years if significant quantities of long-lived radionuclides are not disposed and 10,000 years for sites that do dispose of significant quantities of long-lived radionuclides.

For site stability analyses, the compliance period will vary depending on the type of waste that is disposed. In the final rule, and as it has been since the inception of 10 CFR Part 61 in 1982, site stability is an independent performance objective. Long-term stability may be demonstrated using a risk-informed approach, as discussed in Section 5, that may involve demonstrating that the performance objectives at §61.41 and §61.42 can be met. However, because of the importance of and interrelationship of site stability and disposal facility performance, a regulator may determine that the performance and intruder assessment analyses are not adequate to address protection of public health and safety if a site is expected to experience significant instability that cannot be mitigated.

No changes were made to the guidance as a result of this comment.

F1.2.7 *Comment:* Section 2.2.3; we disagree with the example provided that the quantity and quality of model support could be dictated by consistency with past experiences in similar conditions. The example presented using an engineered barrier is nonsensical and should be removed from the text. Little evidence (if any) is available showing the performance of an untouched engineered barrier beyond 1,000 years, as required by the performance assessment and site stability analysis for sites accepting long-lived radionuclide waste. Because no such example exists, the example is superfluous and licensees will still have to provide a great amount of model support for engineered barriers.

Response: The quantity and quality of model support should be commensurate with the significance of the system/subsystem that is achieving protection. The example provided is simply indicating that if the desired performance of a barrier is commensurate with past experience in similar conditions, that model support would be anticipated to be less, on a relative basis, than if the desired performance is higher. For example, if the design objective of an engineered cover is to limit infiltration to 1 cm/yr, the model support will be substantially less than if the design objective were to limit infiltration to 0.001 mm/yr. Engineered barriers can have varying performance periods, and the model support for each engineered barrier should be performance based. Furthermore, the NRC staff believes the commenter is not correct in their belief that no man-made barriers have achieved performance longer than 1,000 years. Examples are provided in NUREG-1757 (NRC, 2006) of Native American burial mounds that have performed their intended function for hundreds to thousands of years, as well as man-made cementitious materials that are hundreds to thousands of years old. In addition, the NRC staff is not requiring that engineered barriers remain “untouched” as indicated by the commenter.

No changes were made to the guidance document as a result of this comment.

F1.2.8 *Comment:* Section 2.2.3; the guidance that licensees might have to prepare analyses and provide comparisons of results to similar sites modeled by other organizations is not reasonable. This guidance goes against the concept of site-specific analyses, and poses a burden on licensees that have been provided the flexibility to model sites differently than other organizations in order to provide reasonable assurance of site stability and public health protection at their site.

Response: The NRC staff could not find a section or statement in NUREG-2175 that suggests licensees should provide a comparison to similar sites modeled by other organizations. Section 2.2.4 (former Section 2.2.3) lists possible types of model support, “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” and Section 2.2.4.2 provides a model support example performed by the Department of Energy.

No changes were made to the guidance document as a result of this comment.

F1.2.9 *Comment:* Section 2.2.3; the guidance that licensees should perform quantitative analyses for the protective assurance period contradicts the guidance in Chapter 6.0, which states that for dose limits below 0.25 mSv/yr, qualitative or quantitative analyses can be performed. The guidance should remain consistent throughout the entire document.

Response: The protective assurance period concept has not been retained in the final 10 CFR Part 61 rule, therefore, all applicable sections of NUREG-2175 have been modified and/or deleted.

No changes were made to the guidance document as a result of this comment.

F1.2.10 See Comment Response F1.2.S3. This comment was similar in content to F1.2.S3, so the comments were binned together.

F1.2.11 *Comment:* Table 2-1 and Section 2.5.3.1.2.1 are unclear. Please provide clarification if the analyses required are dependent upon the waste concentration as prescribed in Section 2.3.2.4 and provide additional context for the table, including guidance regarding the site characteristic requirements.

Response: The purpose of the guidance in Section 2.3.2.3 Site Characteristics (formerly 2.3.2.4) is to provide an acceptable interpretation of the site characteristics language in §61.7(a)(2), “In choosing a disposal site, site characteristics should be considered in terms of the indefinite future, take into account the radiological characteristics of the waste, and be evaluated for at least a 500-year timeframe to provide assurance that the performance objectives can be met.” Some hydrologic characteristics must be present for 500 years (e.g., sufficient depth to the water table such that groundwater intrusion, perennial or otherwise, into the waste will not occur) whereas others must be absent for 500 years (e.g., tectonic processes). If a licensee were to link the consideration of site characteristics to the waste concentrations as discussed in Section 2.3.2.3, then the incorporated or included FEPs would necessarily be consistent. However, a licensee is not required to interpret the site characteristics language as provided in this document. The approach to analyses timeframes was revised in the final rule, and therefore, the text in many of the subsections in Section 2.3.2 were revised to be consistent. The former Table 2-1 has been deleted from the document.

Changes were made to the guidance document as a result of this comment.

F1.2.12 *Comment:* Section 2.5.3.1.1.1; the iterative process for FEP identification and the consideration of additional FEPs when information is available is unnecessarily burdensome. Staff should provide guidance regarding when it is acceptable for the licensee to stop the iterations. Without such information, the FEP identification process is circular and has no clear end point.

Response: During the performance assessment process, if no new information is forthcoming, there is no need for a licensee to iterate or revise the FEPs analysis. However, if new relevant data or insight has been obtained, the new information would need to be evaluated by the licensee, since it is unknown how the information may affect safety. As with any iterative process, that would involve returning to a previous step within the FEPs analysis. In this case, that step is the systematic screening of FEPs as discussed in Section 2.5.3.1.2.

No changes were made to the guidance document as a result of this comment.

F1.2.13 *Comment:* Section 2.5.3.1.2.1; the quality of the hazard maps in Appendix B related to features and phenomena that can be used to screen FEPs are of poor quality and can easily be misinterpreted by both the regulator and licensee. We recommend removing the hazard maps from the Appendix and as an alternative, providing digital map files (such as ESRI Shapefiles) that allow for viewing on a finer scale.

Response: The hazard maps presented in this appendix provide an illustration of 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 and provide a greater perspective on the expected level of geologic stability based on the location of the potential disposal site. The maps could be used to determine when greater review effort and more technical basis should be expected for the licensee’s site-specific evaluation, and the data

used to produce these maps (see references given for each map) could be applied to perform screening-level analyses of the FEPs.

No changes were made to the guidance document as a result of this comment.

F1.2.14 *Comment:* Section 2.5.4.1; the statement that "a licensee should use scenarios to describe the scenario uncertainty associated with the system" is circular and confusing. We recommend revising the statement or removing it from the text, as it is ripe for misinterpretation by both licensees and regulators.

Response: The statement has been revised and now reads "A licensee may use scenarios to evaluate uncertainty related to different plausible future representations of the disposal site under consideration."

Changes were made to the guidance document as a result of this comment.

F1.2.15 *Comment:* Section 2.5.4.1; the paragraphs describing alternative scenarios is confusing and seems to be in contradiction to the descriptions of FEPs that can be excluded based on regulations. The benefit of developing and analyzing highly improbable scenarios has not been demonstrated and poses unnecessary burdens on both the licensee and reviewer. The requirement should be removed from the guidance.

Response: NUREG-2175 does not provide requirements; it supplies methods or approaches that the NRC staff would find acceptable to assist a licensee in demonstrating a site's ability to meet the regulatory requirements provided in the rule.

Alternative scenarios are based on FEPs that were not excluded during the systematic screening of FEPs. The scenario and conceptual model development process should exclude highly improbable scenarios from consideration. The alternative scenarios should represent less likely, but still plausible, models of disposal site evolution as well as scenarios representing extreme natural events that are within the range of realistic possibilities within the analyses timeframe. A licensee is not required to evaluate scenarios excluded by regulation or implausible alternative scenarios, but could use such scenarios to illustrate the significance of individual barriers and barrier functions.

No changes were made to the guidance document as a result of this comment.

Chapter 3: General Technical Analysis Considerations

F1.3.S1 *Comment:* The majority of Chapter 3 is devoted to describing modeling efforts for radionuclide release and subsequent transport to receptor locations. The reader could benefit from additional context describing the referenced sources. We recommend developing a table, similar to Table 11-4, which references existing guidance or literature by model/topic and also provides a description of the source and its potential use. Given the current layout of the chapter, it would be beneficial to create two of these tables: one for source term modeling and another for transport modeling.

Response: Table 10-5 has been added to provide additional information as requested by the commenter that lists the references related to wasteforms and waste release (source term modeling), including a brief description. A note was added in Section 3.0 referencing Table 10-5 for additional information. A similar table for transport modeling was developed

(Table 10-6), however, Table 10-6 only provides select examples of reference materials because transport modeling is a much broader topic and NRC staff resources were not available at this time to perform a comprehensive evaluation of reference materials. The references provided in Table 10-4 provide pointers to other guidance documents where additional references may be located.

Changes were made to the guidance document as a result of this comment.

F1.3.1 *Comment:* Section 3.1.1, the reference to "Step 8" should be revised and corrected to "Step 9."

Response: Revision made.

Chapter 4: Inadvertent Intrusion

F1.4.S1 *Comment*: Generic scenarios do not inherently account for site-specificity, and numerous viable disposal sites across the country can be seen to demonstrate the inaccuracies in NRC staff's claim on line 28 of page 4-1 that such generic scenarios represent *"normal activities that humans typically engage in…"* Such arbitrary support of generic inadvertent intruder scenarios by NRC staff is also dramatically inconsistent with NRC staff's own claim on line 38 of page 4-11 that "depending on the method used, licensees should provide justification for their selection." Similarly, simple reliance by a licensee on the generic inadvertent intruder scenarios is also contrary to NRC's own guidance on line 20 of page 4-7 that the inadvertent intruder analysis is an "iterative process involving site-specific, prospective modeling evaluations..." Recommend placing greater emphasis throughout the text on the importance of considering reasonably foreseeable and site-specific scenarios at the site location. See table below for lines from the text that we recommend be edited to provide such additional clarity on the scenarios.

Response: While the NRC staff agrees with the commenter that the generic inadvertent intruder receptor scenarios described in Section 4.2 (formerly 4.3.1) do not inherently account for site-specific factors, the NRC staff disagrees with the commenter that greater emphasis is needed on the importance of reasonable site-specific scenarios. Requirements for the inadvertent intruder assessment in 10 CFR 61.13(b) specify that licensees must consider: (i) normal activities and (ii) reasonably foreseeable activities that are consistent with activities occurring around the site at the time the assessment is developed. First, the regulations specify the inadvertent intruder assessment must include normal human activities, including, for example, dwelling construction, agriculture, and water well construction; these activities are expected to occur throughout the country. Exposure scenarios representative of normal activities would generally result in the exposure pathways of most concern. The NRC staff also recognizes that how the "normal activities" cited as examples (i.e., dwelling construction, agriculture, and drilling for water) are carried out may vary across the country depending on local practices and site characteristics, or may not be physically possible at all sites, but provided them as examples of the type of normal activities that should be considered. Second, the regulation also requires the licensee to consider other reasonably foreseeable pursuits; however, the activities need to be consistent with activities and pursuits in and around the site at the time the analysis is performed.

The guidance on inadvertent intruder receptor scenarios in Section 4.2 (formerly 4.3.1) is intended to provide acceptable approaches for developing inadvertent intruder receptor

scenarios that consider both normal activities as well as other reasonably foreseeable activities that are consistent with the activities occurring around the site when the inadvertent intruder assessment is developed. The guidance describes acceptable approaches for demonstrating that both normal and reasonably foreseeable activities have been considered and for limiting speculation on the types of activities an inadvertent intruder may engage in, while ensuring the evaluation of a comprehensive set of exposure pathways. However, the NRC staff recognizes that licensees have flexibility to develop intruder receptor scenarios that consider activities that are consistent with local practices and site characteristics and has provided approaches for modifying inadvertent intruder receptor scenarios based on site-specific factors.

Changes were made to the guidance to reflect responses for each of the specific comments included in F1.4.S1, as noted.

The commenter provided the following additional comments in a table. These comments have been transferred into text for consistency with the remainder of this section.

(1) Section 4.2, page 4-3, line 28, NRC staff correctly discourages development of an unrealistically-wide range of possible inadvertent intruder scenarios that conceivably represent any and all possible future human behaviors. The list of potential changes to intruder barriers in line 28 of page 4-3 should similarly be limited to those that are reasonably expected.

Response: NRC agrees with the commenter that the guidance in Section 4.4 (formerly 4.2) recommending that licensees include *any potential* change to an intruder barrier in the information provided to support an intruder barrier's capability is overly speculative and unnecessary to ensure safety. The NRC staff has revised the guidance in Section 4.4 (formerly 4.2) to clarify that the information licensees should provide regarding intruder barrier capabilities should include significant changes to the barrier rather than any potential change. This ensures that only changes important to safety because of their likelihood and consequences are identified.

Changes were made to the guidance as a result of this comment.

(2) Section 4.2.3, page 4-6, line 25, Subsection 4.2.3 includes a statement that can be misleading to a licensee or reviewer (and not representative of a site's specific erosion processes). It is recommended that the sentence on line 25 of page 4-6 be revised to include context around site specific conditions.

Response: NRC staff disagrees with the commenter that the example of a minimal erosion rate leading to cover reduction over long periods of time is misleading, but has revised Section 4.4.3 (formerly 4.2.3) to clarify the example regarding the impact of erosion in the context of reliance on vegetation to maintain an engineered surface cover.

Changes were made to the guidance as a result of this comment.

(3) Section 4.3, page 4-9, line 8, Considering future distributive events by humans is an understandably challenging undertaking, but not impossible, as suggested by Staff. The statement made on line 8 of page 4-9 should be revised to reflect that the consideration of future disruptive human activities can be evaluated by limiting the scope of analyses to reasonably foreseeable near-term behaviors.

Response: The NRC staff agrees, in part, with the commenter that consideration of human intruder activities can be evaluated by limiting the scope of the inadvertent intruder assessment to reasonably foreseeable near-term behaviors. Because of the uncertainty in future human activities, it is not possible to develop a scientific basis for quantitatively estimating the nature or probability of a future disruptive human activity. Rather than being a challenging undertaking, quantification of the nature or likelihood of a future disruptive human activity could lead to endless speculation. Therefore, 10 CFR 61.13(b) limits speculation by requiring licensees to consider both normal activities and other reasonably foreseeable activities that are consistent with activities occurring around the site. The inadvertent intruder assessment assumes that reasonably foreseeable receptor scenarios, in which the intruder would be expected to receive the greatest exposure to radiation from the waste, occur in order to demonstrate compliance with 10 CFR 61.42. The guidance in Section 4.2 (formerly 4.3.1) provides acceptable approaches for developing reasonably foreseeable receptor scenarios for the inadvertent intruder assessment that consider both normal activities and reasonably foreseeable activities that are consistent with activities occurring around the site when the assessment is developed.

Changes were made to the guidance as a result of this comment.

(4) Section 4.3.1, page 4-11, line 7, NRC's generic inadvertent intruder receptor scenarios were originally created to project inadvertent intruder doses at three generic sites (humid permeable, arid permeable, and humid impermeable). Because of the broad variety of site conditions, climates, meteorologies, geologies, hydrologies, and human behaviors, NRC staff's position that the generic scenarios are conservative and represent reasonably expected human activities in the near future is technically inaccurate and contrary to their own guidance supporting the importance of site-specific analysis (as is reflected in Section 4.3 of the draft Guidance). As such, line 7 of Page 4-11 should be revised to reflect site specific events in the reasonably foreseeable future.

Response: The NRC staff agrees, in part, with the commenter's assertions regarding the generic inadvertent intruder receptor scenarios. NRC staff agrees with the commenter that the generic receptor scenarios were used to provide reasonable bounds on the exposure of inadvertent intruders to radiation from the LLW for the reference disposal facility used to develop the waste classification tables. However, the NRC staff continues to view the generic scenarios, which are consistent with normal human activities and generally result in the consideration of a complete set of exposure pathways, appropriate for consideration in the inadvertent intruder assessment, as required by 10 CFR 61. Licensees are required by 10 CFR 61.13(b)(1) to consider both normal activities, which can be represented by the generic inadvertent intruder receptor scenarios, and reasonably foreseeable activities that are consistent with activities occurring at the site at the time the inadvertent intruder assessment is developed. Consistent with the guidance in Section 4.2 (formerly Section 4.3.1) that is cited by the commenter for amendment, licensees should rely upon the inadvertent intruder receptor scenario of those required that would reasonably be expected to result in the greatest exposure to the inadvertent intruder to demonstrate compliance with 10 CFR 61.42. Therefore, the NRC staff has not revised Section 4.2 (formerly Section 4.3.1) as recommended by the commenter.

No changes were made to the guidance as a result of this comment.

(5) Section 4.3.1.1, page 4-13, line 40, NRC staff presupposes that it is reasonably expected that the site-specific soil and water conditions will support agricultural activities. Without considering what is reasonably expected or site-specific, guidance encouraging inclusion of these exposure pathways in this scenario is simply an arbitrary selection and

cannot unequivocally be considered conservative. As such, the sentence beginning on line 40 of page 4-13 should be corrected to consider reasonably expected pathways.

Response: The NRC staff disagrees with the commenter's assertion that the intruder-construction generic receptor scenario presupposes agricultural activities. The scenario considers exposure pathways that are consistent with construction activities rather than agricultural activities. The exposure pathway that includes the ingestion of contaminated dust or food on which dust has deposited refers to construction workers' meals while onsite rather than agricultural products grown on-site.

No changes were made to the guidance as a result of this comment.

(6) Section 4.3.1.1.3, page 4-16, line 1, 22, Line 1 of page 4-16 should be corrected as, "*The intruder-agriculture scenario is assumed to be possible only if it is reasonably expected that a potable groundwater well can be successfully excavated and that the waste has been degraded to a form that is indistinguishable from soil."* Line 22 of page 4-16 should similarly be revised to read, *"Licensees may adopt the generic receptor scenarios described in Section 4.3.1.1 to demonstrate compliance by providing justification that ~~if~~ the facility's design, operation, and site are suitable for their use and are reasonably represented in the generic scenario characteristics."*

Response: First, while the NRC staff agrees with the commenter that agricultural activities generally require a water supply, NRC staff disagrees that Section 4.2.1.3 (formerly Section 4.3.1.1.3) should be revised to indicate that the intruder-agriculture generic receptor scenario is only possible if a potable groundwater source is viable. Groundwater sources are not mandatory for the consideration intruder-agriculture.

Second, the NRC staff disagrees, in part, with the commenter that licensees need to reasonably represent the facility's design, operation, and site in the generic inadvertent intruder scenarios. While NRC staff recommends the consideration of site-specific factors such as those listed above, licensees have flexibility to develop an inadvertent intruder receptor scenario to demonstrate compliance with 10 CFR 61.42 as described in Section 4.2 (formerly Section 4.3.1).

No changes were made to the guidance as a result of this comment.

(7) Section 4.3.1.1.4, page 4-19, line 3, Given the possible variability in reasonably expected site-specific activities, NRC staff's guidance in the sentence beginning on line 3 of page 4-19 should be revised to reflect reasonably foreseeable site-specific behaviors.

Response: The NRC staff disagrees with the commenter that Section 4.2.1.4 (formerly Section 4.3.1.1.4), which discusses criteria for selecting generic inadvertent intruder receptor scenarios, should be revised to reflect reasonably foreseeable site-specific behaviors. Licensees are required by 10 CFR 61.13(b)(1) to consider both normal activities, which can be represented by the generic inadvertent intruder receptor scenarios, and reasonably foreseeable activities that are consistent with activities occurring at the site at the time the inadvertent intruder assessment is developed. Consistent with the guidance in Section 4.2 (formerly Section 4.3.1), licensees should evaluate the required scenarios and rely upon the scenario that would reasonably be expected to result in the greatest exposure to the inadvertent intruder to demonstrate compliance with 10 CFR 61.42. The guidance cited by the commenter is describing acceptable

DRAFT

approaches for selecting generic receptor scenarios for the inadvertent intruder assessment. Guidance on developing site-specific receptor scenarios is discussed elsewhere in Section 4.2.2 and is not appropriate to include here.

No changes were made to the guidance as a result of this comment.

(8) Section 4.3.2, page 4-26, line 33, It is recommended that NRC staff edit guidance for the review for model abstraction should include the importance of the abstract representation to what may be expected to occur at the site in the near term. Specifically, line 33 of page 4-26 should be amended to focus on the appropriateness of site-specific assumptions, data, and models.

Response: The NRC staff agrees with the commenter that reviewers should ensure that the model abstraction is a reasonable representation of the disposal site for demonstrating compliance with 10 CFR 61.42. The NRC staff has revised Section 4.3 (formerly Section 4.3.2) to ensure reviewers evaluate the reasonableness of the model abstraction given disposal site characteristics.

Changes were made to the guidance as a result of this comment.

(9) Section 4.3.2, page 4-27, line 2, Simple selection of generic codes, models, and parameters does not in and of itself create conservatisms in the analysis. The caution on line 2 of page 4-27 regarding the use of site-specific models and codes should be mirrored to generic codes and models.

Response: The NRC staff agrees with the commenter that justification of conceptual models should be provided whether site-specific or off-the-shelf models and codes are used. NRC staff has revised Section 4.3 (formerly Section 4.3.2) to clarify when licensees should justify the conceptual model for their models and codes.

Changes were made to the guidance as a result of this comment.

(10) Section 4.3.2.2, page 4-30, line 10, The importance of using realistic site-specific characterization should be better reflected in the stated objective in line 10 of page 4-30.

Response: The NRC staff agrees with the commenter that the source term for an inadvertent intruder assessment should reflect the waste disposed at the site. The NRC staff has revised Section 4.3.2 to clarify that the source term should reflect the waste disposed at the site.

Changes were made to the guidance as a result of this comment.

(11) Section 4.3.2.2.3, page 4-34, line 35, The example provided on line 35 of page 4-34 should be clarified to note that the example is only applicable to sites where housing construction is reasonably expected.

Response: The NRC staff disagrees with the commenter that clarification is needed for the example cited in Section 4.3.2.3 (formerly Section 4.3.2.2.3) because the intruder-construction example is simply meant to highlight that receptors for different inadvertent intruder scenarios are typically independent and in no way suggests that a dwelling construction scenario is appropriate for every disposal site. Rather, guidance in Section 4.2 discusses acceptable

DRAFT

approaches for developing inadvertent intruder receptor scenarios including the applicability of intruder activities due to site-specific factors.

No changes were made to the guidance as a result of this comment.

(12) Section 4.3.2.4, page 4-35, line 43, The behaviors listed on line 37 of page 4-35 should be related to expected activities at the site, not generically to ingestion of contaminated waste, soil, plans, and animal products.

Response: The NRC staff agrees with the commenter that exposure pathways may be site-specific rather than a comprehensive list of generic exposure pathways. The NRC staff has revised Section 4.3.4 (formerly Section 4.3.2.4) to clarify that only applicable exposure pathways should be considered.

Changes to the guidance were made as a result of this comment.

(13) Section 4.3.2.4, page 4-35, line 43, The instructions to the assessment reviewer on line 43 of page 4-35 should clarify that the inadvertent intruder behaviors modeled should reflect those reasonably expected.

Response: The NRC staff agrees with the commenter that reviewers should confirm that conceptual models describing human behaviors controlling the amount of exposure are consistent with the receptor scenario and site conditions.

Changes to the guidance were made as a result of this comment.

F1.4.1 *Comment:* Section 4.0, Line 14; Figure 4-1 is inconsistent with the text of Section 4.0. The caption in the Line 14 top circle of the Figure should be revised to *"Demonstrate Compliance with Waste Acceptance Requirements"* to remain consistent with the text.

Response: The NRC has revised the requirements of 10 CFR 61.13(b) in response to comments that the requirements for the inadvertent intruder analyses in the proposed 10 CFR 61.13(b) were vague, circular, and added little value. The NRC staff originally proposed requirements in 10 CFR 61.13(b) that the inadvertent intruder analysis should demonstrate that the waste acceptance criteria developed in accordance with 10 CFR 61.58 will be met, that 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 part of the inadvertent intruder assessment. The first two requirements were analogous to requirements present in the rule prior to this rulemaking. However, the NRC staff agreed with several commenters that the requirement to demonstrate that the waste acceptance criteria are met adds little value because 10 CFR 61.58 also requires that the waste acceptance criteria comply with the performance objectives, which require licensees to conduct the analyses specified in 10 CFR 61.13. The NRC staff also agreed that the proposed requirement to include adequate barriers to inadvertent intrusion added little value because the requirements for the inadvertent intruder assessment also require licensees to 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 intruder barriers are effective. Therefore, the NRC staff has eliminated those proposed requirements and revised 10 CFR 61.13(b) to only require an inadvertent intruder assessment. As such, the NRC staff has eliminated Figure 4-1 and Section 4.1 and revised Section 4.2 from draft NUREG-2175 in the final version of NUREG-2175.

DRAFT

Changes were made to the guidance as a result of this comment and other comments.

F1.4.2 *Comment:* Section 4.2; for added clarity, Section 4.2 could be adjusted to reinforce that the chapter's focus is for protection of an inadvertent intruder.

Response: The NRC staff has relocated Section 4.2 from draft NUREG-2175 to Section 4.4 in the final version of NUREG-2175 and revised the section to focus on identifying adequate intruder barriers and providing a technical basis for the time period over which the intruder barriers are effective.

Changes were made to the guidance as a result of this comment and other comments.

F1.4.3 *Comment:* Section 4.3.1, Line 26 of page 4-11; regarding the assessment that generic receptor scenarios are reasonably conservative should be deleted.

Response: In response to comments regarding inadvertent intruder receptor scenarios required in 10 CFR 61, the NRC staff has revised the requirements to more clearly constrain the types of scenarios considered in the inadvertent intruder assessment required in 10 CFR 61.13(b). Specifically, the inadvertent intruder assessment must assume that an inadvertent intruder occupies the disposal site and engages in normal activities (e.g., dwelling construction, agriculture, and drilling for water) and other reasonably foreseeable pursuits that are consistent with the activities and pursuits occurring in and around the site at the time of development of the inadvertent intruder assessment.

In setting the inadvertent intruder scenario requirements, the NRC staff seeks to balance a need to ensure a reasonable assessment of exposures that could occur should an inadvertent intruder occupy a closed LLW disposal site, and to avoid excessive speculation about the types of activities that humans may engage in far into the future. Constraining exposure scenarios is necessary because: 1) there is limited information available for estimating future human actions and the types of activities that an inadvertent intruder may engage in at times long after closure of the site, and 2) although institutional controls may be durable beyond 100 years, the prudent regulatory approach is to not rely on the effectiveness of institutional controls in the inadvertent intruder assessment to prevent inadvertent intrusion after 100 years. This approach for the specification of the exposure scenarios for the inadvertent intruder assessment provides protection for the inadvertent intruder by ensuring that the most likely activities (i.e., normal activities) of a potential intruder are included in the assessment and other activities (i.e., reasonably foreseeable) are also included in the assessment, as appropriate, and without unnecessary or unsupported speculation (i.e., consistent with specific activities and pursuits occurring in and around the site at the time the inadvertent intruder assessment is conducted).

The NRC staff continues to view the generic receptor scenarios that were used during the initial promulgation of 10 CFR Part 61 and associated with normal human activities, such as dwelling construction, agriculture, and drilling for water, as reasonably conservative for estimating potential radiological exposures to an inadvertent intruder while limiting excessive speculation about future human activities. However, the NRC staff recognizes in NUREG-2175 that for some land disposal facilities, these receptor scenarios may need to be modified based on site-specific conditions to demonstrate compliance with 10 CFR 61.42. Thus, the guidance recommends that licensees use the reasonably foreseeable scenario that results in the greatest dose to the inadvertent intruder to demonstrate that the requirements of 10 CFR 61.42 are met. Further, the NRC staff has provided detailed guidance in Section 4.2 for developing receptor scenarios for the inadvertent intruder assessment including modifying generic intruder receptor

DRAFT

scenarios, determining whether a scenario is reasonably foreseeable, less likely but plausible, or implausible, and how to use these scenarios to demonstrate compliance.

No changes were made to the guidance as a result of this comment.

F1.4.4 *Comment:* Section 4.3.1; the intent behind NRC's justification of generic inadvertent intruder receptor scenarios provided on line 9 of page 4-13 does not automatically equate to their projection of conservatisms and bounding results without adaptation to reasonably-expected site-specific analysis and justifications suggested throughout subsection 4.3.1.2. Rather, the generic receptor scenarios provide conservative bounds for the sites that existed at the time 10 CFR 61 was first promulgated. Such qualifications should be added to the text.

Response: The NRC staff agrees with the commenter that the generic receptor scenarios were used to provide reasonable bounds on the exposure of inadvertent intruders to radiation from the LLW for the reference disposal facility used to develop the waste classification tables. The NRC staff has revised Section 4.2.1 (formerly Section 4.3.1.1) to clarify that the generic receptor scenarios were intended as reasonable bounds for the reference disposal facility. The NRC staff continues to view the generic scenarios, which are consistent with normal human activities and generally result in the consideration of a complete set of exposure pathways, as appropriate for consideration in the inadvertent intruder assessment, as required by 10 CFR 61. Licensees are required by 10 CFR 61.13(b)(1) to consider both normal activities, which can be represented by the generic receptor scenarios, and reasonably foreseeable activities that are consistent with activities occurring at the site at the time the inadvertent intruder assessment is developed. Licensees should evaluate the required scenarios and rely upon the scenario that would reasonably be expected to result in the greatest exposure to the inadvertent intruder to demonstrate compliance with 10 CFR 61.42.

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 site-specific receptor scenarios. The NRC staff also recognizes (as discussed in Sections 4.2 and 4.2.1.4) that the generic receptor scenarios may not be appropriate to demonstrate compliance for certain sites and may need to be modified to account for site-specific factors including site characteristics, facility design, disposal practices, and waste characteristics.

Changes were made to the guidance as a result of this comment.

F1.4.5 *Comment:* Section 4.3.1; we appreciate that NRC staff realizes that when drilling resistance is encountered (as part of the Intruder-Driller Receptor Scenario), a driller will typically adapt by moving the drill rig to a more suitable location. It is recommended that the guidance also note in subsection 4.3.1.1.2 that when extremely low yield or extremely poor quality groundwater is encountered, the driller will also adapt by moving sufficiently far to be located over completely different hydro geologic conditions of higher yield and quality.

Response: The NRC staff agrees that groundwater quality and yield are physical characteristics that would be appropriate to use to modify generic receptor scenarios such as the intruder-driller receptor scenario described in Section 4.2.1.2 (formerly Section 4.3.1.1.2). The NRC staff discussed the use of groundwater quality and quantity in Section 4.3.1.2.1.2 of the proposed NUREG-2175 and has updated the discussion in Section 4.2.1.2 on the intruder-drilling scenario to more clearly direct the reader to the guidance in Section 4.2.2.1.2 (formerly 4.3.1.2.1.2) on using physical characteristics of the disposal site to modify receptor scenarios.

Changes were made to the guidance as a result of this comment.

F1.4.6 *Comment:* Section 4.3.1; since Staff recognizes that prior to construction and dwelling intrusion scenarios, the inadvertent intruder must first excavate a viable production groundwater well, the text should be revised to note that when failing to do so, it can be reasonably expected that neither the construction, dwelling, nor agricultural intrusion receptors will represent site-specific conservatisms.

Response: While the NRC staff agrees that a water supply is necessary for habitation and agriculture, groundwater sources are not mandatory for the consideration of other generic scenarios such as intruder-construction or intruder-agriculture. The NRC staff has clarified Section 4.2.1.2 (formerly 4.3.1.1.2) to indicate that a well is not required to consider other generic receptor scenarios.

Changes were made to the guidance as a result of this comment.

F1.4.7 *Comment:* Section 4.3.1; licensees should only be allowed to adopt generic receptor scenarios after providing justification that facility design, operations, and site are reasonably represented in the generic scenario characteristics. Line 22 should be revised to reflect this position.

Response: The NRC staff agrees that licensees should adopt generic scenarios that are consistent with the land disposal facility's design, operation, and site, as discussed in the guidance in Section 4.2.1.4 (formerly 4.3.1.1.4). However, licensees may adopt generic scenarios that are inconsistent with the design, operation, and site of a land disposal facility for demonstrating compliance with 10 CFR 61.42 if the licensee can demonstrate that the inconsistent generic scenarios reasonably bound the receptor scenarios that are consistent.

No changes were made to the guidance as a result of this comment.

F1.4.8 *Comment:* Section 4.3.1; estimated exposures from generic receptor scenarios might not always be higher than site-specific scenarios. A generic scenario does not automatically equate to conservativism without appropriate consideration and analysis of reasonably expected site-specific conditions. It should be the burden of the licensee to demonstrate, and the reviewer to confirm, whether or not results produced by the application of generic-receptor scenarios are more conservative (e.g., higher projected doses). The statement on line 17 of page 4-17 should be revised to reflect that the generic scenarios represent greater exposure estimates.

Response: The NRC staff agrees with the commenter that estimated exposures from generic receptor scenarios might not always be higher than other reasonably foreseeable receptor scenarios, such as site-specific scenarios. The NRC staff, in Section 4.2.1.4 (formerly 4.3.1.1.4), acknowledges that, in general, the generic receptor scenarios are acceptable for demonstrating compliance if licensees can demonstrate that: (i) the scenarios are suitable for the disposal facility; and (ii) would reasonably be expected to result in greater exposure to radiation from the waste than other reasonably foreseeable receptor scenarios.

No changes were made to the guidance as a result of this comment.

F1.4.9 *Comment:* Section 4.3.1.2; the main advantage of site-specific intruder receptor scenarios is not the flexibility provided the licensee; rather, the main advantage to the licensee and the reviewer is that site-specific intruder receptor scenarios more closely reflect reality. This adds to the degree of confidence that a technically-based and reproducible assessment is achieved. Statements within this section should be edited to reflect the true advantages of site-analyses.

Response: NRC staff agrees with the commenter that using scenarios that reflect site-specific factors enhances confidence that the 10 CFR 61.42 performance objective will be met. The NRC staff has revised Section 4.2.2 (formerly 4.3.1.2) to more clearly articulate this benefit.

Changes were made to the guidance as a result of this comment.

F1.4.10 *Comment:* Section 4.3.2.2, Page 4-30, line 44, because the statement regarding conservative estimates of waste is given without qualification, it is easily misinterpreted by Line 44 reviewers. The statement should be removed or better qualified.

Response: Licensees have flexibility in demonstrating compliance with the performance objectives. The guidance referred to by the commenter attempted to reflect that flexibility is permitted. The NRC staff has revised Section 4.3.2 (formerly 4.3.2.2) to provide an example to clarify that licensees may wish to overestimate inventory for one or more of the technical analyses, such as the inadvertent intruder assessment, if there is sufficient margin to permit an overestimation for demonstrating compliance with the performance objectives.

Changes were made to the guidance as a result of this comment.

F1.4.11 *Comment:* Section 4.3.2.2; this chapter in general is replete with references to "conservatives;" conservative designs, scenarios, estimates, limits, assumptions, parameters. It is inappropriate to urge conservatism at every step, particularly in the case of site parameters. Staff should promote site-specific input parameters and only use (conservative) default values where the input parameters either don't matter (based on sensitivity) or are impossible to obtain. It also is important to recognize that an input parameter that is conservative for one analysis may not be conservative for another.

Response: The NRC staff agrees with the commenter that caution should be used in applying conservative approaches because conservatism may not be absolute, rather it may be relative to a particular analyses or site-specific factor. Further, applying conservatism upon conservatism may lead to suboptimal utilization of safe disposal capacity at a land disposal facility. However, the NRC staff disagrees with the commenter that the guidance in Section 4.3.2 (formerly 4.3.2.2) encourages conservatism in every step of source term development. Rather the NRC staff encourages use of site-specific information, but permits flexibility for licensees to use conservative approaches for source term development (e.g., screening of source term inventory) if appropriately justified.

No changes were made to the guidance as a result of this comment.

F1.4.12 *Comment:* Section 4.3.2.2; the first clarification for appropriate inadvertent intruder assessment source term on line 33 of page 4-34 should be revised to clarify that environmental contamination generated by the inadvertent intrusion is not included in demonstration of the protection of the general public. (Also **F1.4.13** and **F1.4.15**)

Response: The NRC staff agrees with the commenter that receptor scenarios for members of the public and inadvertent intruders are mutually exclusive. The NRC staff has revised Sections 4.3.2.3 (formerly 4.3.2.2.3) and 4.3.3 (formerly 4.3.2.3) to indicate that offsite exposures that are assessed in the performance assessment do not include inadvertent intrusion scenarios, including environmental contamination generated by a hypothetical inadvertent intruder. Rather, transport of environmental contamination caused by an inadvertent intruder should be assessed in the inadvertent intruder assessment, as appropriate.

Changes were made to the guidance as a result of this comment.

F1.4.13 See Comment Response F1.4.12. This comment was similar in content to F1.4.12, so the comments were binned together.

F1.4.14 *Comment:* Section 4.3.2.3; the two examples cited in this section of gaseous diffusion and an intruder well inappropriately imply that these transport mechanisms are always reasonably expected. If non-potable and of extremely low yield, a site's aquifer may not be a viable target for an intruder well. It is suggested to remove the sentence beginning on line 17 of page 4-35.

Response: The NRC staff disagrees with the commenter that that the guidance in Section 4.3.3 (formerly 4.3.2.3) implies that the example transport mechanisms cited by the commenter are always expected. The guidance indicates that onsite transport *may* include these mechanisms. Whether they are significant depends upon the waste disposed and features, events, or processes that influence the migration of radionuclides from the disposal units to the inadvertent intruder. Even for site conditions involving water with poor quality and yield, these transport mechanisms may need to be evaluated. For instance, if depleted uranium is disposed, migration of gaseous radon to the surface may be important depending on the amount of depleted uranium, emplacement strategies, and characteristics of the backfill and overburden. Similarly, while an intruder well may not be possible given the poor water quality, there may be reasonably foreseeable activities occurring in the region at the time the inadvertent intruder assessment is developed, which draw groundwater from wells for other activities, such as using groundwater for industrial dust suppression. Nonetheless, the NRC staff has revised Section 4.3.3 to indicate that transport via groundwater to an intruder well may be necessary to consider if an intruder well is applicable.

Changes were made to the guidance as a result of this comment.

F1.4.15 See Comment Response F1.4.12. This comment was similar in content to F1.4.12, so the comments were binned together.

F1.4.16 *Comment:* Section 4.3.2.4; the statement beginning on line 25 of page 4-35 is misleading. Any contact by anyone (whether on the site or downstream) with waste that has transported away from its original disposal placement will be the result of *"onsite releases from the LLW disposal facility."* The reference to direct contact with waste should be removed.

Response: The NRC staff agrees with the commenter that the use of "onsite releases from the LLW disposal facility" is confusing and erroneous because releases from a LLW disposal facility would, by definition, be offsite. The inadvertent intruder assessment is intended to assess exposure to an inadvertent intruder who occupies the site. Though the NRC staff expects onsite exposures to bound offsite exposures resulting from inadvertent intruder activities, there may be some limited cases where offsite transport results in a larger exposure to the inadvertent

intruder and should be evaluated in the inadvertent intruder assessment, if appropriate, to demonstrate compliance. The NRC staff has revised the guidance in Section 4.3.4 (formerly 4.3.2.4) to correctly state that the dose modeling for an inadvertent intruder estimates potential doses from onsite releases from disposal units.

Changes were made to the guidance as a result of this comment.

F1.4.17 *Comment:* Section 4.3.2.4; the inadvertent intruder methodology summarized on line 30 of page 4-35 should be revised to clarify, "Dose modeling consists of converting radionuclide concentrations generated in environmental media from the inadvertent intrusion onto the licensed site and/or into the waste to dose through various onsite exposure pathways."

Response: Although the commenter did not provide a rationale for the suggested revision, it appears to the NRC staff that the commenter is asking the NRC staff to clarify the intent of dose modeling in an inadvertent intruder assessment. The NRC staff has revised Section 4.3.4 (formerly 4.3.2.4) to clarify the intent of dose modeling for an inadvertent intruder assessment.

Changes were made to the guidance as a result of this comment.

F1.4.18 *Comment:* Section 4.4.; the statement made on line 10 of page 4-37 stating that licensees may assume institutional controls provide durable site protection seems to contradict the entire theme of this chapter, which is a guidance on how a licensee can demonstrate, through analyses not assumptions, reasonable assurance that performance objectives are met. This statement should be eliminated from the text.

Response: The NRC staff disagrees with the commenter's assertion that Section 4.5 (formerly 4.4) contradicts the remainder of the guidance on inadvertent intruder assessment. In Section 4.5 (formerly 4.4), the NRC staff is simply clarifying that licensees may assume that institutional controls are durable and will preclude inadvertent intrusion up to 100 years following transfer of control of the disposal site to the owner, which is consistent with requirements in 10 CFR 61.59. Further, the institutional control period will be determined by the Commission. If the Commission approves an institutional control period shorter than 100 years, then the inadvertent intruder assessment should assume inadvertent intrusion could occur following the Commission-approved institutional control period. If the Commission approves an institutional control period longer than 100 years, 10 CFR 61.59 still requires that licensees may not rely on institutional controls to preclude inadvertent intrusion in the inadvertent intruder assessment beyond 100 years following transfer of control of the disposal site to the owner. The NRC staff has revised Section 4.5 (formerly 4.4) to clarify when institutional controls can be relied upon to preclude intrusion in an inadvertent intruder assessment.

Changes were made to the guidance as a result of this comment.

Chapter 5: Site Stability Analyses

F1.5.S1 *Comment:* The licensee and reviewer would both greatly benefit from the addition of a table or flow diagram that outlines all analyses considerations and timeframes for analyses presented in the rule in 10 CFR 61.44, 10 CFR 61.50(a)(2), 10 CFR 61.50(a)(3), and guidance in Chapter 2.3.2.4, and this chapter.

Response: The NRC staff agrees with this comment. The existing Figure 1-1 (now Figure 1-2) shows the technical analyses (and defense-in-depth) and their relationship to the compliance

DRAFT

period and performance period. A new diagram (current Figure 1-1) was added in Section 1.0 to help illustrate the other timeframes for analyses that are discussed in the document (e.g., 10 CFR 61.41, 61.42, 61.44, 61.50, 61.52, and guidance in Section 2.3.2.3 and Section 5.0).

Changes were made to the guidance document as a result of this comment.

F1.5.S2 *Comment:* Requiring quantitative analyses periods beyond 1,000 years for LLW is unreasonable, unprecedented, and without scientific merit. The use of natural analogues, though helpful to support the design and technical basis for engineered barriers, cannot be used to prove with confidence the stability of a man-made or engineered barrier. Recommend removing requirements to prove site stability past 1,000 years. (Also **F1.5.4**) Section 5.3.1, a commenter stated that if the existing guidance for uranium mill tailings is applicable to LLW disposal sites then the limitations of the guidance should also be applicable.

Response: The NRC staff developed an approach to site stability that has three primary components: 1) ensure site stability for short-lived wastes; 2) allow for the demonstration of stability for the longer term by considering the implications of instability with respect to 10 CFR 61.41 and 10 CFR 61.42; and 3) allow for the regulator to deny or limit disposal if projected instability prohibits modeling of the site.

The current requirement for stability is highlighted as being a cornerstone of disposal. The original regulation is silent on the duration of the stability requirement. An Agreement State could interpret the requirement that stability needs to be ensured for as long as the waste remains hazardous. In this rulemaking, the NRC clarified the requirements in order to ensure consistency. In the final 10 CFR Part 61 rule, the stability requirement in 10 CFR 61.44 applies only to the compliance period, which is 1,000 years for sites that do not contain significant quantities of long-lived radionuclides and 10,000 years otherwise. Stability analyses beyond 1,000 years are only required if a site is disposing of significant quantities of long-lived radionuclides.

The NRC has developed NUREG-1623, “Design of Erosion Protection for Long-Term Stabilization,” (NRC, 2002b), to facilitate design of long-term erosion protection covers, including rock scoring procedures. Chapter 5 of NUREG-2175 discusses other considerations relevant to long timeframes. In addition, advances in computing power have allowed the development and application of complex geomorphological models. A detailed example is provided in NUREG-2175, Appendix E. If a facility is located in an unstable environment, then a licensee may not be able to demonstrate stability. However, if a facility is located in a stable environment, then stability, especially using the performance-based approach as outlined in these regulations, can be demonstrated for the required timeframes. Long-term stability has already been demonstrated for some commercial LLRW disposal facilities in the United States. Under the final rule, stability analyses beyond 1,000 years are only required if a site is disposing of significant quantities of long-lived radionuclides. Considering the recommended approach to site stability, the NRC disagrees that stability beyond 200 to 1,000 years cannot be demonstrated for compliance with §61.44. Further, the NRC notes the standard for compliance with the performance objectives, given in §61.40, is “reasonable assurance,” and compliance does not have to be “proven,” as suggested by the commenter. This analysis is not a prediction of future performance of the disposal site at a point thousands of years in the future, but instead is an evaluation based on the best available knowledge of the disposal site stability.

No changes were made to the guidance document as a result of this comment.

DRAFT

F1.5.S3 *Comment:* The frequent shifts between the requirements and scope of "site stability analysis" and "stability analysis" is confusing and in some instances seem to be used interchangeably and in other instances "stability analyses" seems to reference a larger analysis of which "site stability analyses" are a component. This is also demonstrated in Chapter 2, which provides guidance for analyses required with respect to site characteristics. Recommend making the language consistent throughout both the rule and the guidance.

Response: The terms “stability analyses” and “site stability analyses” were not intended to describe different analyses. References were changed to use the term “site stability analyses.”

Changes were made to the guidance document as a result of this comment.

F1.5.1 *Comment:* Section 5.1; staff should eliminate or provide context for the requirement that licensees that choose to use site-specific scenarios over generic receptor scenarios must consider low frequency natural events in the site stability analyses. An explanation of why generic receptor scenarios "may bound the impact" from these events, and site-specific scenarios would not, is missing.

Response: Clarification has been added to Section 5.1 to explain the guidance provided. Inadvertent 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. Site-specific intruder scenarios that have limited to no direct disturbance of the waste or limited exposure times will commonly produce lower doses to intruders than the doses that may result to the public from disruptive processes or the generic receptor scenarios. The argument that disruptive processes and events do not need to be considered because an inadvertent intruder assessment was performed may be invalid when site-specific intruder scenarios are used.

Changes were made to the guidance document as a result of this comment.

F1.5.2 *Comment:* Section 5.1.1.3; the guidance suggests that site stability, against other disruptive processes, should include climate change for sites accepting waste with long-lived isotopes. The concept that climate change is a disruptive process and should be modeled as such is never referenced in the proposed rule. Furthermore, the guidance suggesting climate change should be considered within the site stability analyses seems to directly contradict guidance in Section 5.1.2 which states that licensees should evaluate natural climate cycling, but are not required to evaluate "anthropogenic climate change." There are no conservative scenarios with respect to the concept of climate change, and any climate change projections cannot be considered reasonably foreseeable. The suggestions around climate change should be stricken from the guidance. This also is in direct conflict with Commission direction that analyses beyond the compliance period ***not*** rely on such assumed conditions: "Given the significant uncertainties inherent in these long timeframes…this performance assessment should reflect changes in FEPs of the natural environment …only if scientific information compelling such changes from the compliance period is available." (SRM-SECY-13-0075)

Response: The guidance in Sections 5.1.1.3 and 5.1.2 are meant to be consistent. The guidance in 5.1.1.3 with respect to climate change is referring to natural variability and cycling in climatic conditions not human-induced climate change. Section 5.1.2 addresses anthropogenic impacts on climate. The text in these sections has been clarified. The NRC staff believes consideration of natural variability and cycling of climate is not in conflict with Commission direction provided in SRM-SECY-13-0075, because natural variability and cycling of climate is well-established by existing scientific information.

Changes were made to the guidance document as a result of this comment.

F1.5.3 *Comment:* Section 5.2.2, The suggestion that refinement of a model with results showing a FEP to be significant could lead to new results showing the FEP is actually insignificant, and thus site stability is proved, should be eliminated from the text. The suggestion encourages the licensee to massage data, parameterization, boundary conditions, and model form to produce satisfactory compliance results.

Response: The text in Section 5.2.2.2 was clarified to state that refinement of the model must be technically justified, so as not to imply that it is acceptable to manipulate the model in the interest of producing satisfactory compliance results.

Changes were made to the guidance as a result of this comment.

F1.5.4 See Comment Response F1.5.S2. This comment was similar in content to F1.5.S2, so the comments were binned together.

F1.5.5 *Comment:* Section 5.3.1; we disagree with the statement "plans to periodically assess the sufficiency" of the guidance around proving engineered barrier stability and "supplement it when necessary." NRC's "*Principles of Good Regulations"* state that regulation should be reliable and not in a state of transition. The proposed actions to reassess the guidance goes against this principle. If Staff lack technical confidence in the actions outlined in the guidance, then the steps should be stricken from the text.

Response: The NRC staff does not lack technical confidence in the approach that is outlined in NUREG-2175, therefore, the statements about assessing the sufficiency of the guidance and supplementing it when necessary have been removed. The NRC staff periodically evaluates the necessity for guidance revisions on an as needed basis.

Changes were made to the guidance as a result of this comment.

F1.5.6 *Comment:* Section 5.3.1; additional content is needed discussing how the requirement to provide a technical basis for engineered barriers is to be incorporated into the overall site stability assessment. The engineered barrier technical basis considerations are only referenced in the discussion of design based approach, yet the text in this section suggests it is a requirement, and thus, independent of the analyses approach used.

Response: Requirements are only provided in 10 CFR Part 61, not in NUREG-2175. As shown in Section 5.2.2 (Approaches for Assessment), on page 5-17, both the design-based approach and the model-based approach should be supported (e.g., technical basis). The model-based approach (i.e., technical assessment) may use engineered barriers. However, instead of the engineered barriers providing complete protection, the degradation and deterioration of the engineered barriers is evaluated. The material in Section 5.3.1 referenced by the commenter is

DRAFT

summarizing guidance in NUREG-1757 that was developed specifically for use of engineered barriers. The important staff recommendation made in these sections is that the technical basis (e.g., model support) should be provided for the performance of engineered barriers that are included in the site stability analysis.

No changes were made to the guidance as a result of this comment.

F1.5.7 *Comment:* Section 5.3.2; we do not agree with the NRC staff that licensees should have to consider "multiple, independent, and redundant barriers" in the design of engineered barriers for long-term waste disposal. Redundancy is demonstrated in the multiple layers of defense including proper site selection, waste inventory, natural barriers and engineered barriers. We believe this suggestion should be removed from the text.

Response: The NRC staff recommends that multiple, independent, and redundant barriers made with high-quality, durable materials be used to provide long-term site stability as an appropriate method to address uncertainty. This guidance is specific to achieving long-term site stability for long-lived waste.

The NRC staff recognizes that different types of elements (e.g., site selection, engineered barriers) may provide redundancy to the system. A licensee should highlight all the elements that help achieve the performance objectives. A footnote has been added to Section 5.3.2 to clarify that redundancy does not necessarily mean multiple replicates of the same components in the design.

Changes were made to the guidance as a result of this comment.

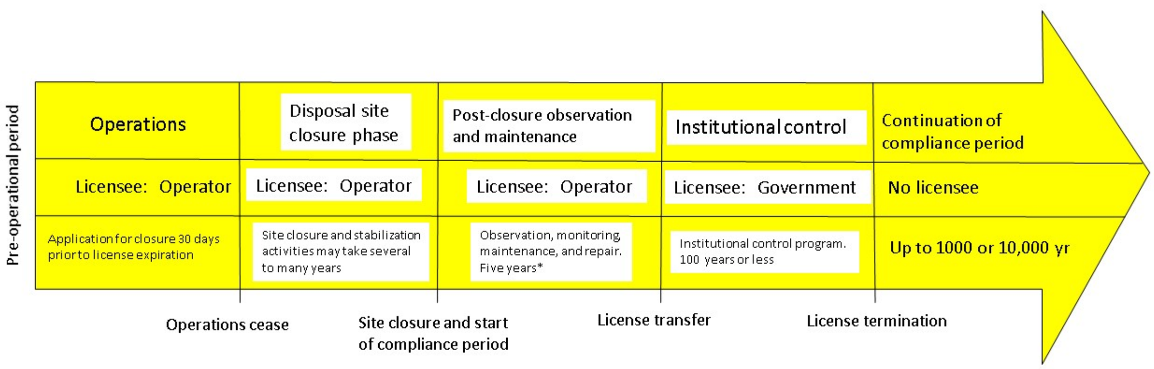
F1.5.8 Comment: Section 5.3.3; we agree with Staff in the benefit of site monitoring and that site monitoring results can be used to assess both site performance and evaluate model predictions and performance. When monitoring results for the institutional control period support initial analyses, the technical analyses should not have to be updated upon site closure.

Response: A new Chapter 9.0, and a new Figure 9-1 has been added to NUREG-2175 that clarifies the site closure process. The site closure phase occurs after operations cease, prior to the period of post-closure observation and maintenance and before the period of institutional controls. There is no requirement to update technical analyses during the institutional control period. There is a requirement to update technical analyses during the site closure phase, as detailed below.

Prior to final closure of the disposal site, licensees are required by 10 CFR 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, including the results of tests, experiments, or other analyses pertinent to the long-term containment of emplaced waste within the disposal site. The closure application must include updated technical analyses that demonstrate there is reasonable assurance that the 10 CFR Part 61 performance objectives will be met. Upon review and consideration of the application for closure, the regulator will issue an amendment authorizing closure if there is reasonable assurance that the 10 CFR Part 61 performance objectives will be met.

After the post-closure period, the licensee may apply to transfer the license to the disposal site owner if the Federal or State government agency which will assume responsibility for institutional control is prepared to assume control and ensure the institutional control requirements will be met (among other requirements, see Section 9.1). The institutional control program must be developed to physically control access to the disposal site following transfer of control from the licensee to the disposal site owner. The institutional control program must provide for environmental monitoring, periodic surveillance, minor custodial care, or other requirements and conditions provided by the regulator.

As discussed in Section 5.3.3, environmental monitoring of a LLW disposal facility is required for the duration of the institutional control period. 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.



Not to scale
* The Commission may approve shorter or require longer periods if conditions warrant

Chapter 6: Protective Assurance Period Analysis

F1.6.S1 *Comment:* Chapter 6 should be eliminated because the three-tiered analyses timeframes approach should be replaced with a two-tiered assessment, with the second tier requiring analyses out to peak dose. Alternatively, the requirement to provide comparisons out to 10,000 years can be eliminated, requiring only the comparison of peak dose of design alternatives. (Also **F1.6.1** through **F1.6.5**)

Response: The protective assurance period has been eliminated in the final 10 CFR Part 61 rule and replaced with a simpler two-tiered approach where the compliance period is 1,000 years if the waste does not contain significant quantities of long-lived radionuclides and is 10,000 years if the waste does contain significant quantities of long-lived radionuclides. Therefore, Chapter 6 of NUREG-2175 has been eliminated.

Changes were made to the guidance as a result of this comment and other comments.

F1.6.1 to **F1.6.5** See Comment Response F1.6.S1. This comment was similar in content to F1.6.S1, so the comments were binned together.

Chapter 7: Performance Period Analyses

F1.7.S1 *Comment:* The rule specifically states that a "qualitative analysis covering a performance period of 10,000 years or more" is required. Contradicting the proposed rule, the guidance requires a "quantitative risk assessment" which is never detailed, but includes a section around "quantitative analyses." We recommend edits to enhance clarity and developing a more detailed approach to better inform licensees in demonstrating performance period compliance when the results from initial screenings necessitate additional analyses.

Response: NUREG-2175 does not provide requirements; it supplies methods or approaches that the NRC staff would find acceptable to assist a licensee in demonstrating a site's ability to meet the regulatory requirements provided in the rule.

The final rule does not specify that the performance period analyses should be qualitative. Section 10 CFR 61.13(e) states "If a 10,000-year compliance period is used for either the performance assessment or inadvertent intruder assessment, the licensee shall assess how the disposal site limits the potential long-term radiological impacts during the performance period, consistent with available data and current scientific understanding."

In most cases, if performance period analyses are necessary, the analyses will be quantitative in some form but the appropriateness of the results will be presented qualitatively because numerical performance standards are not prescribed for the performance period. An appropriate approach for the performance period is to extend the performance assessment from the compliance period.

No changes were made to the guidance as a result of this comment.

F1.7.S2 *Comment:* The requirements to evaluate additional FEPs that are the result of scenarios that have "as low as a 10 percent chance of occurrence over the analysis timeframe" is in direct conflict with the direction given by the Commission in SRM-SECY-13-0075*.* The comments made by Staff in Section 7.3.1 state that the information regarding FEPs will be "limited" and "more susceptible to bias," implying that the additional FEPs considered in this timeframe would not have a scientific basis for supporting the frequency estimates. This clearly is a standard far below "compelling," and based on the direction from the Commission, is inappropriate. It is unclear if these less likely but plausible FEPs represent "key" FEPs as described on page 7-12, line 6. The guidance suggests that the existence of these FEPs might require the licensee to modify conceptual and numerical models, rather than extending calculations or the analyses period. Requiring the licensee to develop alternative conceptual and numerical models for scenarios that lack a defendable scientific basis is unreasonable. We recommend removing the requirements for consideration of less-likely but plausible FEPs.

Response: NUREG-2175 does not provide requirements; it supplies methods or approaches that the NRC staff would find acceptable for a licensee to use in demonstrating a site's ability to meet the regulatory requirements provided in the rule.

DRAFT

The rule language the commenter is referencing with respect to which FEPs to include in the analyses was in place for 10 CFR 61.41(b), the protective assurance period, which has been eliminated as an analysis timeframe in the final 10 CFR Part 61 rule.

This comment refers to the statement on current page 6-6 (former page 7-11) "In comparison to the compliance period, the performance period analyses will be more susceptible to bias because objective supporting information will be more limited." The NRC staff does not agree that this statement implies there would not be a scientific basis for the FEPs considered for the performance period. Rather, it means that greater caution needs to be taken in developing and interpreting the technical basis for the performance period analyses. Licensees should develop adequate technical basis to support their calculations.

As discussed in Section 6.2, Scope of Performance Period Analyses, (formerly Section 7.3), "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. 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." This guidance is designed to provide a reasonable threshold of how to determine what is appropriate to include in the technical analysis for the performance period. The inadvertent intruder assessment in LLW disposal generally has much more limited dilution and dispersion when compared to releases caused by low frequency natural events. Therefore, the inadvertent intruder analysis will likely identify limitations on inventory before they would beidentified by the inclusion of very unlikely FEPs.

No changes were made to the guidance as a result of this comment.

F1.7.1 *Comment:* Section 7.3.3; the recommendation to perform a side-by-side comparison of generic receptor scenarios to the assumed characteristics of the receptors should be limited to the performance period. If this comparison is necessary for other evaluation periods, then the suggestion should be explicitly made in the appropriate sections of the guidance and rule.

Response: The NRC staff believes this comparison is useful for any time period, because the selection of the receptor scenario can have a large impact on the results of the dose assessments. The comparison of the receptors used to the generic receptor scenarios is most useful for the performance period because the timeframes are longer. However, similar text has been added to Section 2.0 to ensure consistency. Licensees are required under 10 CFR 61.13(b)(1) to consider normal human activities as part of the inadvertent intruder assessment. Guidance in Section 4.0 recommends the use of generic intruder receptor scenarios to represent the normal activities and is, therefore, consistent. Because NUREG-2175 is providing guidance not requirements, it is not necessary to add similar language to the rule.

Changes were made to the guidance as a result of this comment.

F1.7.2 *Comment:* Section 7.4; the site-specific conditions that warrant the performance analyses listed in Figure 7-1 should be explicitly written into the guidance.

Response: The approach to analyses timeframes has been revised in the final 10 CFR Part 61 rule and former Section 7.0 (now Section 6.0) has been revised accordingly. In Draft

NUREG-2175, the site-specific conditions that could trigger the need to conduct a performance period analysis were discussed in Section 7.0, page 7-4 (e.g., limited dilution or dispersion, highly-soluble wasteforms). However, as now discussed in Section 6.0, “Performance period analyses are required only if the disposal facility is accepting significant quantities of long-lived radionuclides and has used a 10,000-year compliance period.” Site-specific conditions should be accounted for in the screening analysis performed as described in Section 2.3.2.1 (Compliance Period), which will determine if a site has significant quantities of long-lived waste that warrant a 10,000-year compliance period.

Changes were made to the guidance as a result of this comment.

F1.7.3 *Comment:* Section 7.4 and 7.4.1.1.2; the use of "quantitative risk assessment" should be removed as a quantitative risk assessment is not warranted by the proposed rule. The caption in Figure 7-1 should be revised to read "Qualitative Analyses." (also **F1.7.7**)

Response: The rule does not indicate the specific type of analyses that a licensee should use for the performance period. The NRC staff believes there may be utility in quantitative or qualitative evaluations. In most cases, a qualitative decision will be made based on some form of quantitative information. Because a numerical dose standard is not applied for the performance period, the decision-making will be qualitative. Figure 7-1, now Figure 6-1, was revised to delete the word “quantitative,” and now simply says “risk assessment.”

Changes were made to the guidance as a result of this comment.

F1.7.4 *Comment:* Section 7.4; the guidance to perform additional analyses with bounding values when reasonable averages are available is not reasonable. As stated in the guidance, bounded values, especially those that span many values, can result in illogical and impossible model results. These additional analyses would add nominal value, if any, to the assessment.

Response: Section 7.4 (now Section 6.3) states “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. 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.

To clarify, if defensible central tendency or average values are available, they should be used. However, when information is highly uncertain and supporting information is sparse, the ability of a licensee to appropriately define a defensible central tendency value is hindered. Therefore, it may be necessary, and cost beneficial, to use bounding values. A licensee cannot use unsupported central tendency values.

No changes were made to the guidance as a result of this comment.

F1.7.5 *Comment:* Section 7.4.1.1.1; the required evaluations for screening of potential waste streams should be limited to site-specific and reasonably foreseeable radiation exposure pathways.

Response: NUREG-2175 does not provide requirements; it supplies methods or approaches that the NRC staff would find acceptable for a licensee to use in demonstrating a site's ability to meet the regulatory requirements provided in the rule.

The NRC staff believes the bulleted list of information that a licensee should provide for the screening analyses is appropriate, including a list of the potential radiation exposure pathways at the site and then a description of the most significant pathways for release. However, a clarification has been made in the first bullet to indicate that the pathways considered should be site-specific.

Changes were made to the guidance as a result of this comment.

F1.7.6 *Comment:* Section 7.4.1.1.2; it is unclear what additional analyses can be performed to demonstrate 10 CFR 61.41(c) and 10 CFR 61.42(c) requirements will be met when the screening analyses results are unacceptable. Additional explanation and context than what is currently included is needed.

Response: As described in this section (currently Section 6.3.1.1.1), "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."

Screening analyses are generally simplified and conservative representations of projected disposal site performance. The use of a screening analyses followed by a more detailed evaluation is no different for the performance period than any type of scientific or engineering evaluation. Technical basis should be developed and the conservative models and parameters should be modified to introduce more realism. Though additional dose analyses using refined parameters would be one method to address the issue, licensees could use other methods such as modifying the design, inventory, etc.

No changes were made to the guidance as a result of this comment.

F1.7.7 See Comment Response F1.7.3. This comment was similar in content to F1.7.3, so the comments were binned together.

F1.7.8 *Comment:* Section 7.4.1.1.2; additional content is needed to describe how the analyses in Chapter 6.0 can be applied to the performance period analyses, when there is no dose goal available.

Response: Chapter 6 has been eliminated and the reference to it in previous Section 7.4.1.1.2 has been removed.

No changes were made to the guidance as a result of this comment.

F1.7.9 *Comment:* Section 7.4.1.1.3; additional time periods for analyses are presented, including the 500-year, Class C waste intruder barrier period. The Class C waste intruder barrier period is never explicitly referenced in the proposed rule and as such should be removed from consideration.

Response: The final rule in §61.7(f)(3) "Concepts" under *Waste classification and near-surface disposal* states that "the effective life of intruder barriers should be at least 500 years."

No changes were made to the guidance as a result of this comment.

F1.7.10 *Comment:* Section 7.4.1.1.3; performing cost analyses over multiple timeframes is not justified, and these suggestions should be removed from the guidance. Requiring cost analyses for time periods that pre-date the performance period does not align with the scope of the performance period analyses.

Response: NUREG-2175 does not provide requirements; it supplies methods or approaches that the NRC staff would find acceptable for a licensee to use in demonstrating a site's ability to meet the regulatory requirements provided in the rule.

In order for a licensee to demonstrate that releases have been minimized to the extent reasonably achievable, some comparison to costs and resource expenditures may be useful. In particular, dose comparisons may indicate higher impacts in the performance period compared to the compliance period. Without the resources component of the argument, it may be more challenging to demonstrate that releases have been minimized to the extent reasonably achievable.

No changes were made to the guidance as a result of this comment.

F1.7.11 *Comment:* Section 7.4.1.2; the description of the barrier analyses models the defense-in-depth concept by requiring that multiple, independent, redundant barriers be included in the design and consequentially analyzed. There is no merit in requiring a separate, independent, defense-in-depth analysis, when it is already woven into the requirements for the compliance period analyses.

Response: Section 7.4.1.2 (current Section 6.3.1.2) is not modeling the barrier analyses after the defense-in-depth concept. The section only mentions that the presence of multiple independent and redundant barriers can confound the results of a barrier analysis. "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 barriers." The word "redundant" was deleted from the last sentence. Furthermore, the NRC staff has clarified in the final NUREG-2175 (Section 7.0) that there is no requirement to conduct a separate defense-in-depth analysis, but rather to identify defense-in-depth protections and their capabilities.

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Changes were made to the guidance as a result of this comment.

Chapter 8: Defense-in-Depth Analysis

F1.8.S1 *Comment:* This section requires extensive editorial revision and as such should be revised and published again in draft form for public comment. Our complaint is in the requirement that a separate analytical exercise - a DID analysis - is necessary to demonstrate safety, or that an "analysis" is necessary to demonstrate that defense-in-depth has been accounted for in the siting and design of the site. In addition, we do not believe that a DID analysis was the direction given by the Commission in SRM-SECY-13-0075. Instead, the Commission directed that the rulemaking and guidance document include, "a clear statement that licensing decisions are based on DID protections."

Response: In proposing the defense-in-depth analysis, the NRC did not intend to require a solely quantitative evaluation of defense-in-depth protections because the NRC agrees that some defense-in-depth protections may not be amenable to strictly quantifying the contribution the barrier makes to compliance (e.g., percentage reduction of the dose due to the barrier). For example, procedures or the actions of personnel are not always quantifiable in terms of their impact on dose reduction.

Although the NRC intended that the draft guidance presented in the draft NUREG-2175, which was published concurrently with the proposed rule, would indicate the level of quantification that the NRC expected, the NRC is revising the regulations to further improve the clarity of the requirements that strictly quantitative analyses are not necessary for demonstrating that defense-in-depth protections are provided at a land disposal facility. To accomplish this, the NRC has deleted the proposed § 61.13(f) and added a new § 61.12(o), which clarifies that licensees must identify defense-in-depth protections and describe the protections' capabilities, including a basis for the capability. Thus, the rule allows for a description of the capabilities of barriers (e.g., length of time a cover remains intact, retardation in the saturated zone, release rates from the waste) and does not require a strict quantification of the contribution to performance these capabilities represent.

NUREG-2175 has also been revised to reflect these changes.

Chapter 9: Waste Acceptance

F1.9.S1 *Comment:* The process for using either the generic waste classification tables in §61.55 or the results of the technical analyses in §61.13 as a basis for the WAC is unclear. As previously noted, the distinction between the applications of these two approaches is unclear in the regulation, and the guidance seems to indicate that these two options are not mutually exclusive. In fact, in reviewing this section of the guidance, we are not able to conclude that there is a way for an applicant or a licensee to choose to comply with the classification tables in §61.55 in lieu of developing WAC that would be used for regulating the site. We do not believe this is the intent of the revised regulations and we are not in agreement that this is reasonable.

We suggest that Chapter 9 be split out into two chapters, one dealing with using the old classification system and the other outlining the process for developing the WAC from the technical analyses. A section should be provided at the very beginning of the chapter that discusses the applicability of the new requirements to existing or new sites which desire to accept and dispose of newer waste streams with higher concentrations and quantities of long-lived radionuclides. Provide a clear description of the waste acceptance process for sites that do not dispose of waste containing significant quantities of long-lived radionuclides. As with our

companion comments on the proposed rule, the guidance should be revised to provide current and future disposal sites that do not dispose of significant quantities of long lived isotopes with the alternative to operate under the existing regulatory regime. The guidance should be revised to include a clear discussion of the process for such sites that does not include the preparation and regulatory review of extensive new technical analyses that provide no public benefit or improvement in human health and safety.

Response: While the NRC staff agrees with the commenter that the process for developing waste acceptance criteria should be clear, the NRC staff disagrees with the commenter that the guidance for acceptable approaches to develop allowable limits for specific radionuclides per 10 CFR 61.58 would benefit by splitting into multiple chapters. The regulations permit licensees of near-surface land disposal facilities the flexibility to develop allowable limits for specific radionuclides using the concentration limits in 10 CFR 61.55 or the results of the technical analyses required in 10 CFR 61.13. The NRC does not intend to limit a near-surface land disposal facility licensee's option to one or the other of the two allowable methods. Rather, the NRC agrees that near-surface land disposal facility licensees should be able to use a combination of the two allowable methods as well.

Regardless of the method proposed to develop allowable limits for specific radionuclides, a licensee must conduct technical analyses to demonstrate that the performance objectives will be met because reliance solely upon the concentration limits in 10 CFR 61.55, which are designed to provide protection to an inadvertent intruder whose risk is typically bounded by the concentration of radionuclides in the waste, may not be protective of the general population depending upon the waste disposed and site-specific conditions. The concentration limits in 10 CFR 61.55 were not intended to account for the total activity of certain radionuclides that tend to be more mobile in the environment and migrate off-site. Relying on site-specific technical analyses to demonstrate the performance objectives will be met ensures that the safety decisions with respect to a current LLW disposal facility will be focused on the site conditions and actual inventory that is disposed at the site rather than assumptions regarding a reference disposal site. NRC staff has revised the guidance in Section 8 to clarify that licensees must conduct technical analyses to demonstrate compliance with the performance objectives regardless of whether the concentration limits in 10 CFR 61.55 or the results of the analyses required in 10 CFR 61.13 are used to develop allowable limits for specific radionuclides.

Changes were made to the guidance as a result of this comment.

F1.9.1 *Comment:* Section 9.1; this section does not provide a clear distinction between the technical analyses required to generate site-specific WAC and those required to demonstrate compliance with the classification tables in 61.55.

Response: Regardless of the method proposed to develop allowable limits for specific radionuclides, a licensee must conduct technical analyses to demonstrate that the performance objectives will be met because reliance solely upon the concentration limits in 10 CFR 61.55, which are designed to provide protection to an inadvertent intruder whose risk is typically bounded by the concentration of radionuclides in the waste, may not be protective of the general population depending upon the waste disposed and site-specific conditions. NRC staff has revised the guidance in Section 8 to clarify that licensees must conduct technical analyses to demonstrate compliance with the performance objectives regardless of whether the concentration limits in 10 CFR 61.55, the results of the analyses required in 10 CFR 61.13, or a combination of the concentration limits and results of the analyses are used to develop

allowable limits for specific radionuclides. The required technical analyses are specified in 10 CFR 61.13.

Changes were made to the guidance as a result of this comment.

F1.9.2 *Comment:* Section 9.1.1.1; in general, the language in this section is not clear and should be simplified as much as possible.   This section should include a more detailed summary regarding the development of allowable limits from the technical analyses. Clear guidance is missing, while obvious information is repeated (e.g., paragraph 1 of the section). A flow chart, similar to Figure 9-4 should be created to outline the documentation process for proposed waste classification limits determined using technical analyses in order to satisfy the requirements in §61.13 of the rule. (Also **F1.9.3)**

Response: Section 8.1.1.1 (formerly 9.1.1.1) was revised to include a flowchart that summarizes the process for developing allowable limits from the results of the technical analyses and more clearly describe approaches the NRC staff finds acceptable to meet 10 CFR 61.58(a)(1) for developing allowable limits for specific radionuclides from the results of the technical analyses. Repeated information was deleted as appropriate.

Changes were made to the guidance as a result of this comment.

F1.9.3 See Comment Response F1.9.2. This comment was similar in content to F1.9.2, so the comments were binned together.

F1.9.4 *Comment:* Section 9.1.1.2; the first paragraph in this section includes statements that are in direct conflict with the regulations in 10 CFR Part 61 and are not appropriate for including in guidance. Take for example the last sentence in this paragraph: "Guidance on developing limits on radionuclides not listed in the waste classification tables is also provided in this section." Given that the regulations impose no limits on nuclides not listed in the tables, but rather designate them as Class A waste, it is not acceptable that the NRC would issue guidance that essentially imposes limits on other nuclides.

Response: The NRC staff disagrees with the commenter that the guidance in Section 8.1.1.2 (formerly 9.1.1.2) conflicts with the regulations in 10 CFR Part 61. The new waste acceptance requirements apply to all operating land disposal facilities to ensure that waste acceptable for disposal provides reasonable assurance that the performance objectives will be met. In general, the use of the concentration limits specified in 10 CFR 61.55 remain protective of public health and safety; however, the concentration limits in 10 CFR 61.55 are designed to provide protection to an inadvertent intruder whose risk is typically bounded by the concentration of radionuclides in the waste. The limits were not intended to provide protection of the general population from releases, whose risk is typically affected by the total activity of certain radionuclides that tend to be more mobile in the environment and migrate off-site. Further, all existing land disposal facilities have taken varying amounts of waste containing long-lived radionuclides. The waste concentration limits in 10 CFR 61.55 may not be adequately protective for certain waste streams containing long-lived radionuclides that are classified as Class A by default because concentration limits were not developed (e.g., depleted uranium) for those long-lived radionuclides. Class A waste is considered relatively innocuous because it usually contains the types and quantities of radionuclides that will decay during the first 100 years and will present an acceptable hazard to an inadvertent intruder. Regardless of the method proposed to develop allowable limits for specific radionuclides, a licensee must conduct technical analyses to demonstrate that the performance objectives will be met. The guidance in

Section 8.1.1.2 acknowledges that it may be possible that limits on radionuclides that are not listed in the waste concentration limits in 10 CFR 61.55 may need to be developed for some disposal facilities. As discussed in Section 8.1.1.2, the technical analyses would be used to identify whether limits beyond those in 10 CFR 61.55 would be needed.

No changes were made to the guidance as a result of this comment.

F1.9.5 *Comment:* Section 9.1.1.2, another issue with the language cited in the point above is that it creates a significant unintended consequence of the rule in that it fundamentally undermines the either-or (WAC or classification tables) approach that is created in §61.58. It is anticipated that in the process of developing a WAC to comply with §61.58, an applicant or licensee would have to create a matrix of nuclides, including concentration and inventory limits, that would go beyond the isotopes listed in the tables in §61.55. However, if the result of the new regulations is to require applicants and licensees who propose only to comply with the tables in §61.55 to also calculate limits for nuclides not listed in the tables, then what is the point of the tables? In fact, there would be no circumstance where an applicant or licensee ***could*** comply only with the tables. This is a fundamental change to the status quo that extends far beyond what is suggested by the proposed rule language or has been discussed by the staff in the many public meetings on the proposed rule.

Response: The regulations at 10 CFR Part 61 permit licensees of near-surface land disposal facilities the flexibility to develop allowable limits for specific radionuclides using the concentration limits in 10 CFR 61.55 or the results of the technical analyses required in 10 CFR 61.13. The NRC does not intend to limit a near-surface land disposal facility licensee's option to one or the other of the two allowable methods. Rather, near-surface land disposal facility licensees may use a combination of the two allowable methods as well. Regardless of the method proposed to develop allowable limits for specific radionuclides, a licensee must conduct technical analyses to demonstrate that the performance objectives will be met.

The waste acceptance requirements apply to all operating land disposal facilities to ensure that waste acceptable for disposal provides reasonable assurance that the performance objectives will be met. In general, the use of the concentration limits specified in 10 CFR 61.55 remain protective of public health and safety; however, the concentration limits in 10 CFR 61.55 are designed to provide protection to an inadvertent intruder whose risk is typically bounded by the concentration of radionuclides in the waste. Thus, licensees accepting waste streams similar to those evaluated during the initial promulgation of 10 CFR Part 61 will typically be able to rely on the waste concentration limits in 10 CFR 61.55 for protection of inadvertent intruders. However, the limits were not intended to provide protection of the general population, whose risk is typically affected by the total activity of certain radionuclides that tend to be more mobile in the environment and migrate off-site. Further, the waste concentration limits in 10 CFR 61.55 may not be protective for land disposal facilities that accept waste streams that are significantly different than those evaluated during the initial promulgation of 10 CFR Part 61. Therefore, to ensure public health and safety are protected, licensees must demonstrate that the performance objectives are met via the technical analyses, which may result in limits at some disposal facilities that differ from those listed in 10 CFR 61.55.

No changes were made to the guidance as a result of this comment.

F1.9.6 *Comment:* Section 9.1.1.2; the statement that existing limits "are not intended to provide reasonable assurance that all of the performance objectives are met" and that technical analyses might also be required for sites that rely on the current waste classification limits

negate the purpose of retaining the current classification system. It could be argued that Part 61 licensees always have had to prepare analyses (a performance assessment) in order to demonstrate compliance with §61.41; but compliance with §61.42 ***was*** demonstrated by compliance with the classification tables. The suggested requirements in this section place an unnecessary burden on facilities that intend to rely on the current classification system and not dispose of long-lived radionuclides. A process by which the facilities can simply rely on the current classification system is needed in order to have a true hybrid system, otherwise there is no use for the current classification system. These comments should be eliminated and a discussion of a streamlined process for facilities relying on the existing classification system should be added.

Response: See response to comment F.1.9.5 above.

F1.9.7 *Comment:* Section 9.1.1.3, the concept of "insignificant radionuclides" introduced in this section appears arbitrarily. There is no mention of this concept in the proposed rule and the concept is only implied, but not explicitly referenced in one other place in the guidance, under the Inadvertent Intruder scenario. The sum of radionuclide contribution concept is presented in the rule and Chapter 4 of the guidance. The definition of "insignificant radionuclides" should be added to the proposed rule and discussed in further detail in Chapter 2.

Response: The guidance for the treatment of insignificant radionuclides to develop allowable limits for specific radionuclides in Section 8.1.1.3 (formerly 9.1.1.3) is intended to facilitate a graded approach and allow licensees flexibility in demonstrating compliance with the performance objectives. Licensees may choose not to develop allowable limits for radionuclides that contribute, in aggregate, a projected dose of no greater than 10 percent of the limits prescribed in the performance objective. However, because it is guidance rather than regulation, licensees have the flexibility to develop allowable limits for these insignificant radionuclides if they choose. Further, licensees may propose with adequate justification alternative thresholds for demonstrating radionuclides are insignificant for the purposes of developing allowable limits.

No changes were made to the guidance as a result of this comment.

F1.9.8 *Comment:* Section 9.1.2, the two approaches for waste classification are again intermingled in this section, specifically regarding the applicability of stability requirements, wasteform characteristics, and wasteform test methods. These approaches should be discussed separately. (Also **F1.9.15**)

Response: The regulations permit licensees to use the waste concentration limits in 10 CFR 61.55 or the results of technical analyses to develop allowable limits of specific radionuclides; the regulations require that waste characteristics and container specifications comply with both the minimum requirements set forth in §61.56(a) and any site-specific wasteform characteristics and container specifications developed from the results of the technical analyses used to demonstrate compliance with the performance objectives. Therefore, the intermingling of acceptable approaches for developing wasteform characteristics and container specifications from both the requirements in §61.56(a) and from the results of the technical analyses is appropriate.

No changes were made to the guidance as a result of this comment.

DRAFT

F1.9.9 *Comment:* Section 9.1.2; the three approaches for demonstrating stability requirements should be made obvious to the reader through edits such as highlighting, bulleting or some other mechanism.

Response: The NRC staff has revised Section 8.1.2 (formerly 9.1.2) to highlight the three approaches cited for demonstrating stability requirements.

Changes were made to the guidance as a result of this comment

F1.9.10 *Comment:* Section 9.2; the format of this section is easy to follow, and could be useful to help streamline other sections that have been noted to be unclear or wordy.

Response: The NRC staff appreciates the comment and, as indicated in response to other comments, has revised other sections to improve clarity.

No changes were made to the guidance as a result of this comment

F1.9.11 *Comment:* Section 9.2 and 9.2.1.1; another new term "significant radionuclides" is introduced that is not reference anywhere else in the regulation or guidance. It is suggested that the concept be discussed in Chapter 2. (Also **F1.9.13)**

Response: The NRC staff has removed the term "significant radionuclide" from these sections and refers to radionuclides for which allowable activities and concentrations are developed.

Changes were made to the guidance as a result of this comment

F1.9.12 *Comment:* Section 9.2, Page 9-16 lines 20-22 state: "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." As mentioned previously, these "assumptions and approaches" need to be presented and discussed in the document, since they are so critical to the use of the waste classification system. One example is provided later in the text but additional detail is required.

Response: The NRC staff has revised the guidance to incorporate assumptions and approaches that were used to develop the waste classification requirements specified in 10 CFR 61.55. A summary of the assumptions and approaches from NUREG-0782 are described in the appendices to the guidance. For more details, see NUREG-0782. Sections 4.2.1 (formerly 4.3.1.1), 8.1.1.2 (formerly 9.1.1.2) and 8.2 (formerly 9.2) was revised to direct readers to the appendices.

Changes were made to the guidance as a result of this comment.

F1.9.13 See Comment Response F1.9.11. This comment was similar in content to F1.9.11, so the comments were binned together.

F1.9.14 *Comment:* Section 9.2.1.1.1 and 9.1.1.2; we commend the staff for providing a clear delineation of the processes for using each different basis for the WAC in this section.

Response: The NRC staff appreciates the comment has provided guidance that describes acceptable approaches for developing waste acceptance criteria, including approaches for

DRAFT

developing allowable limits for specific radionuclides from the waste concentration limits in 10 CFR 61.55 or the results of the analyses required in 10 CFR 61.13. NRC staff has also clarified, based on other related comments, that regardless of the method chosen to establish allowable limits for specific radionuclides, licensees must demonstrate that the performance objectives are met.

No changes were made to the guidance as a result of this comment.

F1.9.15 See Comment Response F1.9.8. This comment was similar in content to F1.9.8, so the comments were binned together.

F1.9.16 *Comment:* Section 9.5; mitigation is a concept that is applicable to more than just the WAC. This section should be moved to Chapter 2 and a flowchart would help clarify the process.

Response: The NRC staff agrees that mitigation as a concept is applicable to more than just the waste acceptance criteria. Guidance on mitigation has been moved to Section 9 (formerly 10), which now discusses information associated with disposal site closure. The NRC staff has not added a flowchart for the mitigation process because mitigation is not expected at sites licensed under 10 CFR Part 61 since the regulations are intended to avoid the need for future mitigation, and should mitigation be necessary, it would be highly dependent upon site-specific conditions (e.g., operating history, new information regarding site characteristics or engineered barrier performance) and not amenable to a standardized process as represented by a flowchart.

Changes were made the guidance as a result of this comment.

F1.9.17 *Comment:* Section 9.5; this section refers to the updated technical analyses at closure, which we do not agree with. This section should be modified to explain circumstances when this requirement applies, which as when new unexpected conditions are identified at a site.

Response: The requirements for site closure at 10 CFR 61.28 require licensees to update their closure plan including revised analyses for 10 CFR 61.13. If none of the information from the initial analyses has changed, the original analyses can simply be resubmitted indicating that none of the information has changed. NRC has revised the guidance to address the level of information needed (see Section 9.1). However, the NRC expects that organizations that actively pursue an understanding of the land disposal facility performance over time will likely observe changes in their licensing information used to support their technical analyses. Information from the updated analyses can also be used to support closure activities.

The updates to the technical analyses are intended to capture changes that may have occurred during operations. The requirement to update the analyses when the closure point has been reached is technically sound. Operational experience has shown that an analysis that has been completed decades earlier is generally much different than an analysis that is completed today. Decades of monitoring and observation during operations provides site-specific information that can and should be used by a licensee to support or improve the prior technical analyses of the land disposal facility. It is natural that at the time of licensing there may be some uncertainties. The operational period can and should be used to develop information that can be used to update and refine the licensing analyses, including the consideration of uncertainties in those analyses.

Changes were made to the rule language as a result of this comment.

F.2 Richard Codell

July 23, 2015, ADAMS Accession No. ML15209A564

F2.1 *Comment:* There should be firmer regulatory guidance for the use of criteria other than the maximum dose to an individual such as the inadvertent intruder. This guidance should include criteria such as population or collective dose, ALARA, and geologic stability standards.

Response: The criteria for demonstration of compliance with §61.41(a) and §61.42(a) are individual protection standards and not population or collective dose. However, population dose impacts may be assessed as part of an environmental impact assessment done for a potential disposal action. The final rule provides ALARA requirements (§61.41(a)) as well as a site stability performance objective (§61.44). Chapter 5 of NUREG-2175 addresses the site stability performance objective, which is similar to a geologic stability standard but applied to LLW disposal.

Historically, with 10 CFR Part 61, the term "any member of the public" is used to refer to the receptor for which the dose calculation is performed. For example, see page B-111 in NUREG-1573. The NRC recommends the use of the average member of the critical group as the receptor in performance assessments to demonstrate compliance with dose criteria. The critical group is that subset of the population most likely to be exposed to radiation. For example, in the case of atmospheric releases, the critical group would be individuals living at the point of highest concentrations downwind from the release point. The average member of the maximally exposed group is then compared to the radiological dose limits. "Any member of the public" is not the hypothetical maximally exposed individual within the population subset. The variability in doses between the critical group and the members of public not exposed to radiation is in general much larger than the variability in doses within the critical group. Considering the unknown characteristics of the future exposure group, this simplification is reasonable and warranted. This approach ensures protection of the general population. The purpose of the public dose limit is to limit the lifetime risk from radiation to a member of the general public. The conversion factor used to equate dose into risk is based on data from various populations exposed to very high doses of radiation, such as the atomic bomb survivors, which included individuals of all ages. Therefore, variation of the sensitivity to radiation with age and gender is built into the standards, which are based on a lifetime exposure. For ease of implementation, the radiation standards, which are developed to minimize the lifetime risk, limit the annual exposure that an individual may receive. The member of the public is not limited by regulation to be an adult, though in many cases, for practical application, it is an adult. The radiological dose is a product of the environmental concentrations, transfer pathways, uptake rates, exposure times, and dose conversion factors. All of these factors must be considered together when evaluating radiological doses. For a common receptor scenario, such as the resident farmer, the exposure times and uptake rates are generally higher than most other receptors.

Flexibility in the exposure scenarios is warranted because of the potential for significant variability between sites. Therefore, the NRC has not provided a specific definition for any member of the public. However, NUREG-2175 has been clarified to provide a more detailed discussion of the interpretation of any member of the public.

The NRC acknowledges that a population dose limit would be expressed differently (e.g., as person-rem) than the limit provided in §61.41(a). However, the current rule does not include a

population dose limit, and addition of such a dose limit is considered beyond the scope of this rulemaking. The general population is afforded protection through application of dose limits to any member of the public.

Changes were made to the guidance as a result of this comment.

F2.2 *Comment:* Setting the upper limit of the performance period at 10,000 years is an unfortunate coincidence with the approximate time period for the return of a paleoclimate to the desert southwest, with a much wetter climate including large, deep lakes. This time period is critical to setting a criterion that a site in the Great Basin such as Clive is geologically unstable and, therefore, inappropriate for the disposal of DU in the near surface. The time period should be more generally stated to include the likely return period for a paleoclimate. Future geologic stability, irrespective of dose, should be a siting criterion for disposal of DU.

Response: The approach to analyses timeframes has been revised for the final rule. The compliance period is 1,000 years for disposal of insignificant quantities of long-lived radionuclides, and 10,000 years if significant quantities of long-lived radionuclides are disposed. The performance period begins after the compliance period and a performance period analysis is required if a compliance period of 10,000 years is used. For disposal of large quantities of DU, the compliance period will be 10,000 years and a performance period of 10,000 years will apply with no set upper limit. Therefore, the return of a paleoclimate should be evaluated. However, 10 CFR Part 61 does not include numerical dose standards for the performance period.

For site stability analyses, the compliance period will vary depending on the type of waste that is disposed. In the final rule, and as it has been since the inception of 10 CFR Part 61 in 1982, site stability is an independent performance objective. Long-term stability may be demonstrated using a risk-informed approach, as discussed in Chapter 5, that may involve demonstrating that the performance objectives at §61.41 and §61.42 can be met. However, because of the importance of and interrelationship of site stability and disposal facility performance, a regulator may determine that the performance and intruder assessment analyses are not adequate to address protection of public health and safety if a site is expected to experience significant instability that cannot be mitigated.

No changes were made to the guidance as a result of this comment.

F.3 John Tauxe, Neptune

July 24, 2015, ADAMS Accession No. ML15211A060

F3.1 *Comment:* Section 1.1.2; it remains unclear how the safety case is to be constructed. It seems that this is a collection of documents and analyses required to demonstrate adequate protection of public health, but the mechanics of how all these analyses are to be collected into a Safety Case is lacking. Is the Safety Case a document that serves as a wrapper for the performance assessment, intruder assessment, defense-in-depth analysis, etc. Please provide clarity on what is expected in terms of a license applicant's submittal.

Response: See response to comment **F1.1.1**, under comments submitted by Energy Solutions.

F3.2.1 *Comment:* Section 1.1.4.1 and 3.0; an issue with section 1.1.4.1 is that it addresses modeling for the sake of modeling. Modeling should be performed in some context of the decisions to be made. Compliance decisions are insufficient for evaluating the efficacy of

a disposal system and optimizing disposal, which are critical for maximizing use of these precious resources (disposal systems). Modeling should be performed to evaluate options, in which case a framework for options analysis is needed within which the modeling implied here should be performed. The beginnings of addressing this appear in Item (10) of Section 1.1.4.1, but this does not go far enough.

Response: The modeling performed for 10 CFR Part 61 is not “modeling for the sake of modeling” but modeling for the sake of making a compliance decision. Compliance with the performance objectives is a safety decision, not an optimization of a resource problem. However, licensees are not prohibited from and are encouraged to optimize disposal resources if it can be done in a safe manner.

No changes were made to the guidance as a result of this comment.

F3.2.2 *Comment:* Section 1.1.4.1 and 3.0; Bullet (8) uncertainty addresses the contaminant transport part of a PA, whereas the exposure part is better addressed through variability (population characteristics per EPA's description of probabilistic risk assessment). Variability should not be used directly in the projected behavior of the system except to inform the uncertainty in the mean estimates.

Response: When the variability can be established, then the NRC staff believe it should be used to inform the uncertainty in the mean estimates. However, in many components of the performance assessment there will be uncertainty in the variability. Variability may be known to exist but how it should be represented may be uncertain. As discussed in Section 2.7.4, NRC does not require a particular type of analysis (i.e., deterministic or probabilistic), but does highlight some of the challenges and pitfalls associated with each.

No changes were made to the guidance as a result of this comment.

F3.3 *Comment:* Section 1.1.4.2 and 4.0; consider this text from p. 1-5: "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." This simply is not true.

Using IA to establish WACs is a mistake. This will not allow the nation to effectively use the limited disposal facilities that we have, and will arbitrarily cause disposal facilities to function sub-optimally. WAC should be based on site-specific PA, not on IA. (also **F3.25**) The IA is not useful for making decisions about radioactive waste disposal.

The IA should be folded into the PA, and intruders should be addressed as potential receptors just like any other MOP, with probability of occurrence included in the analysis.

Response: While, in principle, the significance of human intrusion might be ideally assessed using a risk-based approach considering both the probability of intrusion and the associated consequences, any projections of the magnitude of intrusion are by necessity dependent on assumptions that are made about future human behavior. Since no scientific basis exists for predicting the probability of future human actions, the NRC does not believe that it is appropriate to include the probabilities of such events in a quantitative performance assessment that is to be compared with the dose constraint for protection of the general population. Rather consideration of a reasonable set of receptor scenarios against a separate dose limit, which

recognizes that an inadvertent intrusion is unlikely, but possible, affords a reasonable level of protection should an inadvertent intrusion occur.

No changes were made to the guidance as a result of this comment.

F3.4 *Comment:* Section 1.1.4.3 and Chapter 5.0; the point of the stability analysis is not clear and needs metrics in order to be evaluated. We strongly suggest that risk (dose) be used to evaluate stability, along with cost. That is, this should be folded into the PA, with potential options for stability evaluated. Stability for the sake of stability, removed from the context of risk, is not useful except for appearances. (Also **F3.30**) If an unstable site produces no added risk, then why should we care? We agree that all the processes that contribute to loss of stability, as discussed in the subsections of 5.0, should be included in the FEPS analysis, and if they survive screening, in the PA modeling. The consequences to receptor dose will then naturally fall out of the PA. Lines 17-19 (of 5.0) contain an adequate definition of "stability" that should be used as a definition in 10 CFR 61.2. The current definition in 61.2 is self-referential and wholly inadequate.

Response: The definition of stability was revised in the final 10 CFR Part 61 rule to state:

"Stability means the capability of the disposal site (e.g., wasteform, disposal containers, and disposal units) to maintain its shape and properties to an extent that will not prohibit the demonstration that the land disposal facility will meet the §61.41 and §61.42 performance objectives and will, to the extent practicable, eliminate the need for active maintenance after site closure."

For site stability analyses, the compliance period will vary depending on the type of waste that is disposed. In the final rule, and as it has been since the inception of 10 CFR Part 61 in 1982, site stability is an independent performance objective. Long-term stability may be demonstrated using a risk-informed approach, as discussed in Chapter 5, that may involve demonstrating that the performance objectives at §61.41 and §61.42 can be met. However, because of the importance of and interrelationship of site stability and disposal facility performance, a regulator may determine that the performance and intruder assessment analyses are not adequate to address protection of public health and safety if a site is expected to experience significant instability that cannot be mitigated.

Stability could have been folded into the other performance objectives, but the NRC staff decided to leave it separate to highlight that there may be circumstances where instability may prohibit adequate modeling of a site.

No changes were made to the guidance as a result of this comment.

F3.5 *Comment:* Section 1.1.4.4 and 6.0; we support the use of releases as a long-term performance metric rather than doses. We support the statement: "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..." What is refreshing here is the use of the term "releases," which makes the analyses reminiscent of the Containment Requirements for transuranic waste in EPA's 40 CFR 191. Given the long time frame of these analyses, it is good to be rid of the term "dose," since this is burdened with the unfathomable uncertainties of human behaviors past 10,000 years. Later discussions of the protective assurance period analyses sometimes revert to the use of

the term "dose" as a performance metric, and we encourage that such references be modified to make reference to "releases" instead.

Response: The protective assurance period has been eliminated from being an analyses timeframe, therefore; the sections referenced in the comment have been removed from the NUREG. However, references to “minimize releases of radioactivity” are specified with respect to the performance period.

No changes were made to the guidance as a result of this comment.

F3.6 *Comment:* Section 1.1.5 and 9.0; at the end of section 1.1.5 is a bulleted list of requirements for a certification program. Missing from this list is the characterization of uncertainty in waste documentation. In our experience, having developed PA models for over half a dozen radioactive waste disposal sites, the uncertainty in inventory is the most significant and most irreducible variable in the model. Unless positive steps are taken to require generators to characterize uncertainty in their wastes, this will continue to be the case. Without this uncertainty characterization, decisions about waste acceptance and disposal site operations will continue to be clouded, leading to inefficiencies in the *defacto* national radioactive waste disposal program and a squandering of the precious resources that are waste disposal facilities.

Response: The NRC staff agrees with the commenter on the importance of understanding uncertainty in waste characterization. Thus, 10 CFR 61.58(b) specifically requires that waste characterization methods shall identify the characterization parameters and acceptable uncertainty in the characterization data. NRC staff has revised Sections 1.1.5 and 8.2 (formerly 9.2) to further highlight the need for understanding uncertainty in waste characterization.

Changes were made to the guidance as a result of this comment.

F3.7 *Comment:* the term "risk-informed" is promising, but that not enough information is provided as to how a risk-informed decision should be made. This guidance sets up an approach based on *ad hoc* decision making – some people get together and make a decision. We have the technology to do better than that. "Risk-informed" would have meat if it were framed in a decision analysis context. This is the paradigm shift that is needed to support effective decision making, and remove the confusions that stigmatize this industry. (Also **F3.33**)

Response: There is no prohibition on employing a decision analysis context to risk-inform the application of the low-level waste disposal regulations. However, a decision analysis context or framework is not required. Some decisions associated with simpler facilities and more traditional low-level waste may not benefit significantly from the application of decision analysis. The decision the regulator is attempting to make is whether a facility is reasonably protective of health and safety. Decisions about optimizing design or the utilization of a facility are under the purview of the licensee.

No changes were made to the guidance as a result of this comment.

F3.8 *Comment:* Section 2.2.1; it is unclear what is meant by "some amount of incompleteness in the data may be overcome by appropriately accounting for parameter uncertainty." This indicates a confusion of ideas.

Incompleteness of data leads to greater uncertainty in the sense that there is less data than there might have been otherwise. Parameter uncertainty is based on the amount of data available. Hence, this sentence makes no sense. We suggest it be deleted.

Note also that there are other ways to obtain data to support a specific parameter. These include model abstraction and meta analysis. It's not clear what is meant by "last resort" for expert elicitation. There is nothing inherently problematic with expert elicitation. If "last resort" is meant to imply cost-effectiveness, then this should be stated, but it is incorrect to imply that expert elicitation is not a reasonable approach, which seems to be the intent here.

Response: Lack of information or limited information is the primary source of uncertainty for most inputs (and the models themselves) in a performance assessment. For example, consider experimental observation. If there is only one measurement, the uncertainty that should be prescribed to the parameter derived from the experimental observation is going to be much larger than if hundreds of measurements are obtained. Uncertainty should not be confused with variability. Lack of data is the converse of “large amount of data available.”

Expert elicitation is appropriately stated as being less preferred because it is a subjective source of information rather than an objective source of information. Experts can have high error rates even on matters that are more well-known and less complex than performance assessments. Subjective sources of information are associated, in general, with higher error rates than objective sources of information.

No changes were made to the guidance as a result of this comment.

F3.9 *Comment:* Section 2.2.2; the final sentences of Section 2.2.2 state, "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." This is not the role of uncertainty analysis – this is the role of *sensitivity analysis,* which is not discussed much in this document. Uncertainty analysis (UA) addresses uncertainty in the decision. Sensitivity analysis (SA) addresses what drives the outcome and how to reduce uncertainty. There should be a separate and distinct discussion of sensitivity analysis to clarify the different roles of UA and SA.

Response: The NRC staff agrees that there is a difference between uncertainty analysis and sensitivity analysis, and will remove the second sentence on parameters quoted in the comment so as not to distract from the first quoted statement. However, the NRC staff did not address the treatment of parameter uncertainty in depth in NUREG-2175 because the techniques are comparatively well documented and widely published so that analysts or statisticians have relatively easy access to various techniques (e.g., statistical sensitivity analysis based on Monte Carlo sampling, regression methods, or distribution partitioning intercept methods). However, NRC staff agrees that a subsection is needed to briefly discuss such techniques and how they fit in to the overall uncertainty analysis, and to provide references of papers and publications that describe and explain such techniques in detail.

Section 2.7.4.1 on parametric uncertainty and sensitivity analyses was added to NUREG-2175 to address this comment.

F3.10 *Comment:* Section 2.2.2.1; it is not clear that uncertainties are greater for long-lived waste. In fact, some things become certain for long-lived waste even if the exact timeframe is uncertain (the exact timeframe is not very relevant in deep time). For example, in the Clive

DU PA Model, it is relatively clear (not uncertain) that in 2 million years (My) all waste disposed below grade will be part of an organically developed geologic repository (i.e., under about 300 m of sediment). Whereas, for short lived waste disposed above grade, for example, the waste will be dispersed at some point well before 2 My. DU does not actually reach secular equilibrium until about 2.1 My—there is a lot of certainty then, even if the exact time is not known. The sentence needs to be qualified.

Response: The examples given in the comment on the increased ensuredness of an unlikely event actually occurring given a sufficiently long timeperiod may be true; however, as a general statement, calculations involving long-term performance are associated with more uncertainty than forecasts on the evolution of a site in the short-term future. The probability of an event may preclude that event from being considered as an influencing force at a site in the short-term, however, not from the long-term. As the rate of change, direction, and interaction between processes become more influenced by additional FEPs as time progresses, the evolutionary directions a site may take become more numerous.

No changes were made to the guidance as a result of this comment.

F3.11 *Comment:* Section 2.2.2.1.1; a challenge here is that probabilistic modeling essentially considers a continuum of scenarios. For example, climate variation spans a continuum of possibilities, which can be handled through probabilistic modeling (i.e., through probabilistic specification of input parameters). Scenarios are best left for truly discrete distinctions that cause the system to move in a different direction, and not for changes that are unknown but possible across a continuum.

Response: A continuum of scenarios that includes climate variations likely could be handled through probability modeling, as the commenter suggests. However, using the climate example cited by the commenter, if evidence indicates that a different climate is plausible that could affect dose results, any receptor scenarios would need to be compatible with that plausible alternative scenario. Receptors would need to be living a lifestyle that matched that climate and new environment. For example, increased water at and near the disposal site might change the groundwater flow regime in a fundamental way so that another conceptual model may need to be considered, i.e., the water table may rise and groundwater may then flow in a fractured unit closer to the ground surface and allow quicker contaminant transport versus a slower transport in a deeper porous hydrogeologic unit with a lower hydraulic conductivity. Subsequently, the location and depth of a well – used in a receptor scenario would be adjusted to fit the new conditions.

No changes were made to the guidance as a result of this comment.

F3.12 *Comment:* Section 2.2.2.1.2; in this case, different distinct models could be proposed. So, model uncertainty should involve evaluation of distinct models (for example, there are several models of tortuosity in the literature – which one is best for a specific PA and site?) For this type of model uncertainty, some model averaging could be brought in to support the PA effort. Conceptual model uncertainty, on the other hand, can probably be handled for the most part through uncertainty characterization of the parameters. Simulation uncertainty is different yet again, and should be separated into its own section. Model uncertainty, conceptual model uncertainty, and simulation uncertainty are really all different enough that they need separate sections.

Response: The NRC staff agrees that there are different types of model uncertainty including the uncertainty in the conceptualization of the system, the uncertainty in its mathematical representation, and the uncertainty in the solution of the mathematical representation. While separate sections could be written for each, it is the conceptual model uncertainty that is probably the dominant type of uncertainty in a performance assessment and is less analyzed than other types of model uncertainty. It may be possible to handle conceptual model uncertainty through the characterization of parameters; however, features and parameters from one conceptual model that are represented in a numerical model may not be the same feature and processes found in an alternative conceptual model and may not be represented in the original numerical model, so a sensitivity analysis would not be possible. For example, porous flow and transport may be part of the conceptual model; however, there may be a line of evidence for an alternative conceptual model that has fracture flow as the dominant means of water flow. This may entail different groundwater volumes, velocities, and directions and the consideration of unique transport properties that may be difficult to represent with a given set of parameters based on the original conceptual model.

No changes were made to the guidance as a result of this comment.

F3.13 *Comment:* Section 2.2.2.1.3; parameter uncertainty is not reducible or irreducible. Parameter uncertainty is simply reducible by collecting more data/information. It could be argued that variability is irreducible, but variability should not be applied to the fate and transport model (except to support development of uncertainty estimates – more or less standard deviation (variability measure) divided by n). This is always a difficult discussion because of the number of literature articles on the subject, most of which cause greater confusion. It would be better to define terms here, and, since these are statistical/probabilistic issues, that should be the basis for the definitions. Note that the approach to parameter uncertainty depends on how the simulations are performed.

Most models involve drawing random numbers at the beginning of time, and then using those as deterministic values through the model's propagation in time. If, instead, random numbers are pulled at each time step, then some further thought needs to be put into how parameters are probabilistically specified. Note also that in a probabilistic risk assessment (which is essentially what a probabilistic PA is), the exposure parameters need to cover the potentially exposed population, in which case they are based on variability rather than uncertainty. If the terms uncertainty and variability are not palatable here, then at least it should be recognized that some parameters (fate and transport leading to concentration assessment) are addressed through upscaling (distributions of means, essentially, which implies characterizing uncertainty), whereas, some are addressed without upscaling (because PRA is about addressing all members of the population, not the average member).

Response: The NRC staff attempted to find the appropriate balance in NUREG-2175 between overall completeness of the methodologies for conducting technical analyses for 10 CFR Part 61 and between providing too much detail such that the guidance becomes unwieldy and difficult to use. For this topic, treatment of data uncertainty, techniques are comparatively well documented and widely published so that analysts or statisticians have relatively easy access to various techniques. For example, the *History and Value of Uncertainty and Sensitivity Analyses at the Nuclear Regulatory Commission and Center for Nuclear Waste Regulatory Analyses* (Mohanty et al, 2011) documents the uncertainty and sensitivity analysis knowledge acquired over the past 20 years by the NRC staff and the Center for Nuclear Waste Regulatory Analyses (CNWRA®) staff. Granularity and upscaling of performance assessment models are discussed, as well as, traditional techniques for parameter sensitivity. Advanced and special-case

sensitivity techniques include genetic algorithms with cascaded variable selection, regionalized sensitivity analysis, iterated fractional factorial design, and parameter tree and distribution partitioning intercept methods. However, the NRC staff agrees that a subsection is needed to discuss all aspects of uncertainty analysis, and to provide references of papers and publications that describe and explain such techniques in detail.

Subsection 2.7.4.1 on parametric uncertainty and sensitivity analyses has been added to the document to address this comment.

F3.14 *Comment:* Section 2.2.3.1.4; applying conservative values *does not address uncertainty.* It addresses misplaced value judgments. It obfuscates effective decision analysis and decision making. This document would benefit from further sections that specifically address upscaling and correlation. Why do large variances only require careful treatment in an intruder analysis—this makes no sense. Since transfer factors are applied to fate and transport components, they address uncertainty and upscaling. The degree of skew in the supporting data (or expert opinion) is mitigated to some extent through upscaling. It is important that the fate and transport parameters (those that are used to lead towards estimation of concentrations in various media, locations, etc.) are established as upscaled (averaged) quantities. The care that needs to be taken in upscaling must address the dilution effect mentioned. The role of inter- and intra-site values is not made clear. This is an issue of ability to generalize data from one site to another. In general, we probably do not assign sufficient uncertainty to that generalization, but a combination of data from another site and expert opinion can be used to at least address some of the missing uncertainty. Note again that this must be in terms of uncertainty in the upscaled values. Conservative values should not be used. One is reminded of the question asked Charles Babbage: "Mr. Babbage, if I provide you the wrong inputs, can your machine produce the right output?" His answer was, "I fail to understand the confusion of ideas that led to such a question." And yet, that is what is proposed here. If there are no data, then use expert elicitation. If there are no experts, then put a wide distribution in, and let the sensitivity analysis determine if it matters. If it matters, then put more effort into it (at greater cost.) If it doesn't matter, then leave it alone and move on.

Page 2-10, line 24: Replace "uncertainty" with "sensitivity." This is an example of the confusion between the UA and SA concepts that exists in this document.

If this section is to remain, it should be re-cast as a section on data generalization issues, instead of being presented as an uncertainty example.

Also, the NRC Regulatory Guide 1.109 (NRC 1977) should not be cited as an example, as it is quite dated and has values in it with no support.

Response: The NRC staff agrees in part and disagrees in part with the commenter. The comment has two main parts: (1) the use of conservative values and (2) data generalization.

The NRC staff disagrees that the use of conservative values represents a misplaced value judgment, rather staff believes it is an appropriate approach to use in regulatory analysis. The commenter stated:

> "If there are no data, then use expert elicitation. If there are no experts, then put a wide distribution in, and let the sensitivity analysis determine if it matters. If it matters, then put more effort into it (at greater cost.) If it doesn't matter, then leave it alone and move on."

At the point of the process where it is determined that missing or limited data matters, the only option is not to put more effort into developing what the parameter should be, at greater cost. The cost may not be justified or it may be prohibitively large. A globally conservative value may be possibly assigned to demonstrate that safety can be achieved. The NRC staff recognizes that this may obfuscate the “true” performance of the system and it may make optimization of the use of the facility difficult. However, the regulatory requirements are not to optimize the use of the facility, but rather to demonstrate that public health and safety will be protected.

In the example given for transfer factor uncertainty, the guidance was not limited to only the intruder assessment, as indicated by the commenter. Data generalization is a very significant issue for performance assessments and upscaling must be done very cautiously. Upscaling has the potential to eliminate important spatial and temporal variability that may be a site-specific feature important to the assessment. The guidance example discusses inter- and intra-site variability to highlight the potential for mischaracterization of variability as uncertainty. Consider the following example:

Site A, B, and C have characterization data for the distribution coefficient for uranium. Within the range of values generated for each site is temporal and spatial variability, as well as measurement uncertainty. In addition, the distribution coefficient itself is a simplified representation of what may be complex geochemical and mineralogical interactions. The developed distributions are shown below. A researcher takes the data from all three sites to produce a single “generic” distribution. Now a new Site D is to be developed. The developers wish to simulate uranium transport but have no measurements, what should they do?

Site A – 30 samples, normal distribution, mean = 80 ml/g, standard deviation (SD) 20 ml/g
Site B – 60 samples, unclear distribution type, mean = 120 ml/g, range from 1.3 to 400 ml/g
Site C – 20 samples, lognormal distribution, geometric mean = 30 ml/g, geometric SD = 3

Combining the data from the three distributions yields the curve in red. Calculating the mean of each site distribution and the confidence in the mean and then combining the data yields the curve in green. First and foremost, the data may not be representative of Site D at all. Second, averaging point estimates to a site-wide mean value and then combining removes large portions of the variance in the original data. It is making the assumption that all of the data is random and uncorrelated. In fact, in this example, the data from Site B was actually three different zones of Kd’s perhaps representing different mineralogical units or geochemical conditions. The overall data should have reflected zone 1 of Site B that had all measured Kd’s less than 5 ml/g. Generalization of data can be very important.

The example on transfer factors in NUREG-2175 was attempting to communicate that when a generic dataset representing a large number of observations at different locations is used for a site-specific analysis, the results must be interpreted very carefully if the generic dataset is important to the decision. The variance in the overall distribution will contain contributions from inter- and intra-site variability as well as other sources of variance such as measurement error.

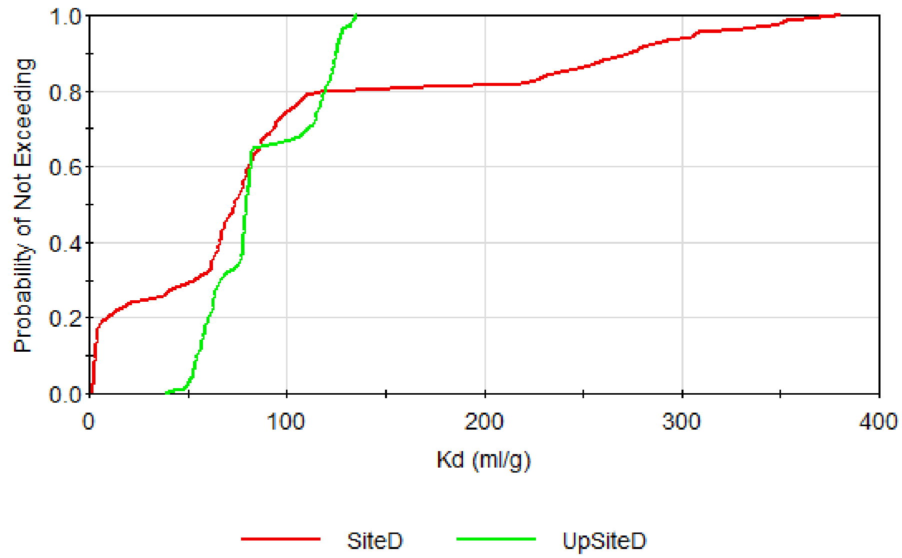

Figure A Example of Different Data Representations for Uranium Kd

Changes were made to the guidance document as a result of this comment.

F3.15 *Comment:* Section 2.2.3.1; peer review does not belong in a section with expert judgment and elicitation. Peer review is a form of model support (which could be described in Section 2.2.3), whereas expert judgment and elicitation are methods to specifying a model (akin to data collection). These are different concepts that do not belong in the same section.

Response: The NRC staff disagrees with this comment. Former Section 2.2.3.1 (current Section 2.2.4.1) is addressing the use of experts for different purposes in waste disposal. This section references a similar document for HLW disposal (NUREG-1563, “Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program,” (NRC, 1996)), in which peer review and expert elicitation were discussed in the same document. Therefore, the NRC staff believes it is appropriate to discuss them in NUREG-2175 in the same section. The differences between the different types of uses of experts is noted in the text.

No changes were made to the guidance document as a result of this comment.

F3.16 *Comment:* Section 2.2.4.1; receptor scenarios should be based on site-specific knowledge, and projected into the future based on that knowledge (i.e., conditioning on current knowledge). The point is made more effectively on page 2-16, line 11, but should be reinforced in this section. This is also an example of how use of the term "FEPS" works better than merely "FEP" (Also, editorial comment).

We strongly recommend that the traditional term "FEP," for features events, and processes, be replaced with the term "FEPs," which includes receptor scenarios. Receptor scenarios are not merely the result of the assessment of other FEPs – they are fundamental to the scoping of analyses, and deserve "top billing," in the principal acronym. The development of modeling scenarios indeed is the product of the analysis of FEPs, as the document discusses, but such scenarios are also dependent on the receptor scenarios that are identified as being fundamental to the scoping of a PA. As an example, section 2.6, Conceptual Model Development, should include receptor scenario development as a foundation leading to CSM development. This

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guidance is a great opportunity to start making this point more clear to the PA community. Please consider replacing all instances of "FEP" with "FEPS."

Response: Receptor scenarios should be based on site-specific knowledge if the projected future is fairly well known and unchanging. However, if, for example, there is strong evidence that an area has a cyclic climate pattern and the regulatory compliance period is associated with long-lived radionuclides, the site-specific conditions could change for the receptor during the time of consideration as could the receptor scenario.

Current regional land use and other local conditions in place at the time of the analysis will strongly influence exposure pathways that are considered significant for disposal sites with relatively short-lived radionuclides. That is, not much emphasis is placed on the potential evolution of the disposal site. Fixed receptor or exposure scenarios can be developed once an understanding is obtained on how a disposal system functions, and it is conceivable that such exposure scenarios be included in the analysis itself, making it an analysis of features, events, processes, and exposure scenarios (FEPS). However, LLW disposal sites that will contain significant quantities of long-lived radionuclides will need to have their performance assessed for longer timeframes. Conditions can change during timeframes of such lengths so that exposure pathways and receptor activities, and subsequently exposure scenarios, may also change. In such a case, the changing exposure scenarios are dependent on the future evolution of the disposal site, i.e., from the FEPs analysis and scenario development, and cannot be part of the FEPs analysis.

The NRC agrees with the commenter that receptor scenarios are fundamental; however, the NRC does not agree that many scenarios do not naturally result from an analysis of features, events, and processes alone. The natural evolution of a site is assumed to occur without human interference. The NRC's position is that it is too speculative to postulate on the effects of potential human technologies and activities on the evolution of natural systems. Using information and data gathered during characterization to develop scenarios of a site's future and evaluating which receptor activities are plausible in those scenarios adheres to NRC's positon. At the same time, it is NRC policy to allow licensees flexibility in the methodology used to meet the performance objectives.

No changes were made to the guidance as a result of this comment.

F3.17 *Comment:* Section 2.3.1; although the data quality objectives (DQO) process has some problems in its implementation, philosophically it is a sound rendition of the scientific method. It basically starts with the question, "What decision needs to be made?" The same should be true here. The decisions include compliance, but much more importantly, should include optimization of waste disposal: the best cover design, best placement of waste, best institutional controls, etc. Rather than DQOs, it would be better if this were all framed in a decision analysis construct. More specifically, it should be framed as a stakeholder-engaged structured decision making process. This is the paradigm shift that is needed so that the public is protected rationally and defensibly, while allowing for the disposal of waste in responsible ways.

Response: Although the data quality objectives process may be a philosophically sound rendition of the scientific method, the performance assessment process laid out in Chapter 2 is an approach that the NRC staff would find acceptable to meet the regulatory requirements provided in the final rule, and is sufficient for this guidance document. However, many aspects

of the process described in this comment are similar to what is being discussed in the assessment context (Section 2.3) and the performance assessment approach in Chapter 2 should result in a disposal system with components whose performance would ensure public health and safety and met the regulatory requirements. A decision analysis construct can be performed to attempt to find the most optimal cover design, placement of waste, institutional controls, etc., however, this is a decision to be made by the licensee and is not a requirement in the final rule.

No changes were made to the guidance as a result of this comment.

F3.18 *Comment*: Section 2.3.2; evaluation against these time periods is unfortunate. It is not clear why radionuclides are treated so differently technically than wastes that will never change and might pose greater hazards (lead, arsenic, asbestos), and other wastes that have effective decay sequences that lead to more hazardous waste (PCE to TCE to VC, for example). There are several reasons why 1,000 years is too long – these include reasonableness of evaluating dose beyond 200 to 300 years, change that is inevitable, vastly increased uncertainty with time, and economic considerations (e.g., discounting, which is a natural phenomenon) coupled with the need for long term financial planning. There is a great confusion of regulations and guidance across different radioactive waste issues, let alone expanding further to include hazardous waste regulations. There are occasional opportunities to make real effective change. This is one of them, but this is not being achieved.

Response: A proper technical analysis needs to be performed to determine if projected doses are below the established limits. Most modern LLW disposal facilities will reduce or eliminate releases of radioactivity to the environment for extended periods of time. For most arid sites, significant releases will be delayed longer than 1,000 years and the majority of sites currently operating are in arid locations. In addition, 10 CFR Part 61 applies to all types of LLW, not just LLW resulting from nuclear power plant operations. For instance, this rulemaking was initiated, in part, to address the disposal of large quantities of depleted uranium, which presents a hazard extending well beyond 1,000 years.

Performance assessments are not predictions of a future result but rather they are designed to assess potential future performance. Current experience and knowledge associated with engineered near-surface disposal facilities is limited to a few decades, but it is anticipated that the scientific community will continue to invest in developing better understanding of the long-term performance of engineered designs. The objective of safety analyses for LLW disposal is not to model or calculate only those things that are known precisely. Safety standards should not be weakened in the face of large uncertainties. The safety analyses must consider uncertainties including those uncertainties associated with long-term performance. If the uncertainties are too large or cannot be defined, then the risk is unknowable and safety cannot be assured. Not all LLW is suitable for near-surface disposal. The NRC's requirements will ensure that the viability of near-surface disposal will be determined for each LLW stream.

No changes were made to the guidance as a result of this comment.

F3.19 *Comment:* Section 2.3.2.3; the reference to "releases" (p. 2-23, line 24) is appropriate, but that positive is quickly negated with mention of the metric "peak annual doses that are projected to occur after 10,000 years" (p. 2-23, line 30, and again on p. 2-24, line 15). We recommend sticking to the "releases" or "activity concentrations or fluxes" concept, as invoked again at the top of p. 2-24.

Response: The performance period metrics may include dose, concentration, fluxes, or others. Different stakeholders and Agreement State regulators may find value in using a variety of metrics and the regulatory requirements are intended to afford that flexibility. This guidance is consistent with the regulatory requirements.

No changes have been to the guidance as a result of this comment.

F3.20 *Comment:* Section 2.3.2.4; the term "C" in the equations on p. 2-25 (lines 26 - 28) requires a careful definition in order for it to be implemented consistently. Is this the activity (or mass) concentration in disposed wastes at the time of closure? At 1,000 years after closure, accounting for decay and ingrowth? Some other time? Is it radionuclides that are in the original waste volume, or would it account for radionuclides that have been transported elsewhere in the environment? These questions must be answered, or an analyst will be forced to guess what the intent is.

Response: The text has been clarified to provide greater explanation to the term “C” in the equations referenced. The term “C” is the disposal site average concentration of long-lived isotopes. As discussed in Section 2.3.2.1.1.1 the calculation of disposal site average waste concentration may include the waste, disposal units, backfill materials, and materials between disposal units but does not include the buffer zone. It is to include the activity in the waste at the time of disposal, but account for peak concentrations resulting from decay/ingrowth for those short-lived isotopes that produce long-lived alpha emitting progeny.

Changes were made to the guidance as a result of this comment.

F3.21 *Comment:* Section 2.5; the use of stylized scenarios is potentially problematic. Their use implies conservatism, which is essentially misplaced value judgments. It is perfectly fine to make conservative decisions, but it is not fine to make important decisions based on conservative models. Conservatism should be addressed through value judgments, so that it is properly characterized. FEPS screening should take place, and should be based on an understanding of probability and consequence. Refer to *The Foundations of Statistics* (Savage, 1954). This reference lays out exactly how models should be built, what considerations should be given, etc. It addresses both marginalization (ignoring distinctions between events), and conditioning (ignoring events), and offers useful insight for how a FEPS screening process could be implemented.

Response: NRC staff did not recommend the use of stylized scenarios as part of the scenario development process in NUREG-2175. Alternative scenarios are based on FEPs that were not excluded during the systematic screening of FEPs. The scenario and conceptual model development process should exclude highly improbable scenarios from consideration. The alternative scenarios should represent less likely, but still plausible, models of disposal site evolution as well as scenarios representing extreme natural events that are within the range of realistic possibilities within the analyses timeframe. A licensee is not required to evaluate implausible alternative scenarios, but could use such scenarios to illustrate the significance of individual barriers and barrier functions.

The sections in NUREG-2175 that present approaches to systematic screening of FEPs includes subsections on probability and consequences, i.e., Sections 2.5.3.1.2.2 and 2.5.3.1.2.3, respectively.

No changes were made to the guidance as a result of this comment.

F3.22 *Comment:* Section 2.5.3.1.2.2, Page 2-42, last bullet, lines 3-4: It's interesting that FEPSs that do not have information or data, and nothing is known about the process, are included automatically here. There are many processes that are never included in a PA because we don't know how to include them. For example: microbiological degradation of containers, colloid transport. However, NRC implies here that they should be included.

Uncertainty associated with probability: Possibly most FEPSs evaluations would have to be evaluated based on expert elicitation. It is difficult to see how the FEPSs can be evaluated probabilistically otherwise. At the very least, expert elicitation is likely to play an important role. Perhaps this can be noted and referenced to the section on expert elicitation. Some more explanation is needed here. The Yucca Mountain Project evaluated the probability of volcanic hazard as part of the FEPSs process (at very large cost). This was done by building a complex model that led to (uncertain) estimates of this probability.

Response: Plausible FEPs that have scarce information or data should not be excluded if the potential negative consequences to performance are high. Most performance assessments do try to incorporate features and processes for which the consequences can be high and some line of evidence prevents them from being excluded. An analyst should not ignore a FEP that has the potential to significantly affect performance because they don't know how to include them at that moment. As discussed in comment F3.12, certain types of conceptual model uncertainty could be handled through parameter representation, e.g., in order to represent colloidal transport, altering the range of distribution coefficient values for certain contaminants so as to accommodate the transport potential of a range of clay particle concentrations may be sufficient to simulate the process.

Expert elicitation could be part of a FEPs evaluation, but should only be used if progress on the performance assessment process is being hindered. In addition, expert elicitation should be limited to FEPs that could have an impact on performance. Additional information on expert elicitation can be found in NRC's Branch Technical Position on the use of expert elicitation (NRC, 1996). As far as the Yucca Mountain project is concerned, an igneous scenario was included in the performance assessment due to the potential consequence. Although no complex model was built to estimate the probability of volcanic hazard in the Yucca Mountain area, Formal Expert Elicitations did document that the range of igneous activity probabilities was not sufficiently low enough to exclude from the assessment.

No changes were made to the guidance as a result of this comment.

F3.23 *Comment:* Section 2.7.4; this section discusses, among other things, the concept of SA, but subtly mischaracterizes it in saying that "...the purpose of sensitivity analysis is to evaluate uncertainty and variability in the assessment." (p. 2-61, lines 16-17.) The purpose of an SA is to identify which model input parameters contribute most to that uncertainty. Further discussion on this page revolves around the flawed approach of on-at-a-time (OAT) SA, which will not allow one to thoroughly evaluate the contributions of input parameters to uncertainty in the model results. The text on p. 2-62, while a bit garbled, attempts to put OAT-SA in its appropriate context, identifying its limitations, but this OAT-SA approach needs to be more forcefully deprecated.

Response: A sensitivity analysis can be used to evaluate the contribution of variability to the model output, such as by simulating a waste layer with homogeneous properties or by comparison with a geostatistically generated representation of the property values. This is a form of focused sensitivity analysis. Sometimes variability is known, whereas in other cases, the variability is known to exist, but the particular values are unknown. Some low-level waste disposal concepts may be relatively simple and the modeling representation of those concepts may also be relatively simple. In these cases, the OAT-SA can have value and can be used without significant error in resultant decisions. However, the NRC staff agrees with the commenter that it can be a significant challenge to interpret OAT-SA results with a more complex, probabilistic model.

No changes were made to the guidance as a result of this comment.

F3.24 *Comment:* Section 3.2.7; it is interesting to see the reference to "Anthropogenic direct releases..." (p. 3-16, line 41.) This would suggest that releases of radionuclides that might occur from intrusion into wastes should be considered as part of the contaminant transport in a model. For example, drill cuttings brought to the surface should be incorporated into the larger contaminant transport calculations, as they could result in exposures to not only the drilling crew but to other receptors as well, perhaps much later in time. We agree with this approach.

Response: The NRC staff agrees in part with the commenter that direct releases due to intrusion should be evaluated to demonstrate the performance objectives. The NRC has promulgated a performance objective to protect an inadvertent intruder, but does not require protection of an advertent intruder. Advertent intruders are aware of the hazards associated with intrusion and would be expected to take appropriate precautions to reduce exposures. Thus the NRC only requires evaluation of exposures to inadvertent intruders. Guidance in Section 4.0 describes acceptable methods for evaluating exposures resulting from direct releases from inadvertent intrusion. As discussed in the guidance, transport of contamination from direct releases should be considered on the disposal site rather than off-site. Exposures to releases from an inadvertent intruder for an on-site intruder would generally be greater than for an off-site member of the public because transport tends to disperse contaminants in the environment. Licensees may also need to consider other scenarios that might lead to a larger exposure as a result of a direct intrusion scenario. For instance, a well driller may contact the waste during drilling and spread some portion of the waste on or in the vicinity of the ground surface leading to later exposures associated with agriculture (i.e., intruder-agriculture scenario). The guidance referenced by the commenter in Section 3.2.7 explains that anthropomorphic direct releases are evaluated in the inadvertent intruder assessment, which considered exposures on the disposal site.

No changes were made to the guidance as a result of this comment.

F3.25 See Comment Response F3.3. This comment was similar in content to F3.3, so the comments were binned together.

F3.26 *Comment:* Section 4.3.1.1; a generic IA is of even less use than a site-specific one. At lines 12-13 on p. 4-13, the statement is made that "Loss of intuitional control is not expected..." Quite the opposite is true. Loss of IC is certain-it is only a matter of when control is lost.

Response: The regulatory basis for the original 10 CFR Part 61 assumed that inadvertent intrusion occurred following a cessation of an active institutional control period administered by the land owner or custodial agent. Institutional control of the disposal site was expected to occur beyond the active institutional control period, however, control becomes increasingly difficult to ensure at longer times and thus it is not relied upon to ensure safety. Consistent with the basis for the original 10 CFR Part 61, the regulations at 10 CFR 61.59 impose land ownership and institutional control requirements that are intended to limit the potential for intrusion into a closed land disposal facility. However, the NRC recognizes that while the institutional controls are expected to be durable, uncertainty in the durability over long time periods exists. Thus, the regulations only permit licensees to rely on the controls for up to 100 years. NRC staff has clarified expectations for institutional controls in Section 4.2.1 (formerly 4.3.1.1).

Changes were made to the guidance as a result of this comment.

F3.27 *Comment:* Section 4.3.1.1.2; the drilling referred to in this scenario is for water wells. It should be made more generic to include drilling for petroleum resources (gas and oil) as well.

Response: The regulations at 10 CFR 61.13(b) require that the licensee's inadvertent intruder assessment assumes that an inadvertent intruder occupies the disposal site and engages in normal activities (e.g., dwelling construction, agriculture, and drilling for water) and other reasonably foreseeable pursuits that are consistent with the activities and pursuits occurring in and around the site at the time of development of the inadvertent intruder assessment. Section 4.2.1.2 (formerly 4.3.1.1.2) describes the generic well drilling scenario used to inform the waste classification system that was developed during the initial promulgation of 10 CFR Part 61. Intruder activities represented by the generic receptor scenarios, such as the water well drilling scenario, are reasonable for representing normal activities in the inadvertent intruder assessment. In the case of drilling for water, water is essential for many human activities. However, the regulations also require licensees to consider other reasonably foreseeable pursuits that are consistent with activities occurring in and around the site at the time the inadvertent intruder assessment is developed. Therefore, drilling for petroleum resources may need to be considered for sites where exploration or extraction is occurring.

Changes were made to the guidance as a result of this comment.

F3.28 *Comment:* Section 4.3.2.2; included in an exposure source term should be not only radionuclides in the original waste layers, but those that have migrated upwards into the column above the waste, towards the ground surface. These, especially the decay products of ^{222}Rn which may have diffused upward, can add significantly to the receptor dose.

Response: NRC agrees with this comment and has included guidance in Section 4.3.2 (formerly 4.3.2.2) discussing the need to consider both direct contact receptor scenarios in which the intruder directly exposed to the waste as a result of their activities on site and indirect receptor scenarios in which the intruder is exposed to radionuclides from the waste that have migrated away from the disposal units (e.g., via radon diffusion and groundwater transport).

Changes were made to the guidance, but not as a direct result of this comment.

F3.29 *Comment:* Section 4.3.2.2.1; the last paragraph on p. 4-31 has problems. It says that licensees "may conservatively assume no decay." This is at odds with the very next

DRAFT

sentences, which recognizes the "impacts of significant progeny", and that "radioactive decay can result in significant ingrowth of progeny at future times." ("at future times" should be deleted, as it is redundant.) As we know, using depleted uranium as an example, assuming no decay is in some cases definitely not conservative. The following sentence attempts to make this clear, but should be changed from "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." to "For example, activities from depleted uranium will increase for more than two million years due to ingrowth of shorter-lived and more highly mobile decay products."

Response: NRC staff intended to indicate that licensees may assume no radioactive decay occurs prior to the inadvertent intrusion, if it is conservative. NRC staff has revised Section 4.3.2.1 (formerly 4.3.2.2.1) to clarify the intent.

Changes were made to the guidance as a result of this comment.

F3.30 *Comments* **F3.30** through **F3.32** (Section 6.2.1.1 through 6.2.1.3, alternatives analysis and minimization analysis), pertain to the protective assurance period, which has been deleted and is no longer an analysis timeframe that licensees must evaluate. Therefore, the entire Chapter 6 of NUREG-2175 has been removed from the document. A portion of F3.30 is also responded to in F3.4.

F3.33 *Comment:* p. 7-1, line 26 contains the statement, "The level of detail in the assessment should be risk-informed." It is not clear at all what that means. The term risk-informed has been used for several years now, but without definition. Metrics are needed to make decisions. What are the risk-informed metrics in this case?

The footnote to Table 7-1 says "Any isotope [sic] that is to be disposed of in sufficient quantifies should be considered as part of the LLW PA inventory." Please define "sufficient quantities."

Top of p. 7-4: It is not clear why more expert judgment is needed in this case. This seems to be a continued "knock" on expert elicitation as a "poor man's data analysis." This is not the case. Expert elicitation should be used when it is most cost-effective to do so. Since these long-term models essentially project today's conditions into the future, it is not clear why longer term modeling requires more expert elicitation. Most of the input distributions will not change from the 1,000-year model.

Further, why would simple conservative analyses be used? The model is already set up for 1,000 yr (unless there are new events) – it is trivial to project out the same model for 10,000 yr or longer. This section should be re-written. As former Commissioner Magwood once said a problem we face in waste management is "conservatism on top of conservatism on top of conservatism." Conservatism has no place in modeling for important decisions. Its place is in specification of value judgments in a complete decision analysis, based on realistic – not conservative-analysis. Otherwise this section seems to ramble some, and might benefit from some reorganization and deletion of material.

p. 7-4, line 28: Change "is variability in hydrogeology" to "may be variability in hydrogeology." There are sites where hydrogeology is simply unimportant.

Response: The text in Section 6.1 (previously Section 7.1) that follows the statement about the assessment being risk-informed explains what that terminology means in the context of the performance period assessment, including providing a table as to how to risk-inform the

performance period analyses. The primary driver prior to completing the analyses is consideration of the concentration and quantities of long-lived waste. Because the analyses process may be iterative, after some assessment is done, the results of the assessment may be used to refine and focus effort on those aspects of the assessment that are most important to the performance period output metrics.

The “sufficient quantities” has been removed from the footnote to Table 7-1 (now Table 6-1), as all isotopes to be disposed should be considered. However, after consideration, some isotopes may not be present in large enough quantities and may be eliminated from further evaluation in the assessment. Staff’s recommendation for how to determine if a site contains “significant quantities” of long-lived radionuclides is discussed in new Section 2.3.2.1.1.

The issue of expert elicitation is addressed in response to comment F3.8. The issue of conservatism is addressed in the response to comment F3.14. The issue of risk informing is addressed in F3.7.

The text regarding variability has been removed from the section as a result of other changes to the document.

Changes were made to the guidance as a result of these comments.

F3.34 through F3.37, minor edits

Comment example: The word “of” is not needed in a phrase such as “LLW was disposed of”. The NRC staff agree with this edit and made this change in the document.

Response: Document revised as recommended, in most instances.

F.4 Webinar

May 20, 2015, Transcript ADAMS Accession No. ML15261A615

F4.1 *Comment:* Betsy Forinash, page 16. Which of the analyses must be conducted when the tables are used and which apply to development of site-specific waste acceptance criteria for particular or unusual waste streams?

Response: The new waste acceptance requirements apply to all operating land disposal facilities to ensure that waste acceptable for disposal provides reasonable assurance that the performance objectives will be met. Regardless of the method proposed to develop allowable limits for specific radionuclides, a licensee must conduct the technical analyses required by 10 CFR 61.13 to demonstrate that the performance objectives will be met. NRC staff has revised the guidance in Section 8 to clarify that licensees must conduct technical analyses to demonstrate compliance with the performance objectives regardless of whether the concentration limits in 10 CFR 61.55 or the results of the analyses required in 10 CFR 61.13 are used to develop allowable limits for specific radionuclides.

Changes were made to the guidance as a result of this comment and other comments.

F4.2 *Comment:* Roger Seitz, page 37-38. Are you requiring a demonstration of defense-in-depth or maybe something more?

Response: The NRC is revising the regulations to further improve the clarity of the requirements that licensees must identify defense-in-depth protections and describe their capabilities, including demonstrating that defense-in-depth protections are provided at a land disposal facility. To accomplish this, the NRC has deleted the proposed 10 CFR 61.13(f) and added a new 10 CFR 61.12(o), which clarifies that licensees must identify defense-in-depth protections and describe the protections' capabilities, including a basis for the capability. Thus, the rule allows for a description of the capabilities of barriers (e.g., length of time a cover remains intact, retardation in the saturated zone, release rates from the waste) and does not require a strict quantification of the contribution to performance these capabilities represent. The NRC staff has revised NUREG-2175 to reflect these changes.

Changes were made to the guidance as a result of this comment and other comments.

F4.3 *Comment:* John Greeves, page 38. My view is that the proposed regulation has a lot of how-to, which I call guidance, in it. How did you differentiate between what should go in the regulation and what should go in the guidance? For example, 61.13 was a few paragraphs now it is like 16. How did you decide how much of that needed to be on the regulation versus guidance?

Response: The requirements provided for LLW disposal represent the key aspects of performing a performance assessment (e.g., consider uncertainties, provide model support, and develop scope). The requirements provided are not "how-to guidance," they are the fundamental elements of a performance assessment.

Section 61.7 provides a narrative or the context for the requirements that follow in the regulation. However §61.7 does not provide specific regulatory requirements, and therefore, is not expected to produce a regulatory burden. Text was added or modified in §61.7 to ensure consistency of the approach for the new regulation and the original 10 CFR part 61 regulation. Some text in §61.7(e) has been revised for clarity. In addition, §§61.7 and 61.13 were streamlined to reduce the amount of detail in the rule. Important examples and recommendations are contained in NUREG-2175.

No changes were made to the guidance as a result of this comment.

F4.4 *Comment:* Diane D'arrigo, page 39-40. Using the performance assessment, do you have some percentage likelihood that the estimated dose will be achieved or not exceeded? And does it matter that the performance period doesn't go to the peak dose? I know you're not using the same meaning of the word "peak," but the performance assessment doesn't have to go all, or does it go all the way out to the peak dose?

Response: A likelihood that the estimated dose will be achieved or not exceeded is not required by 10 CFR Part 61, however, this information could be generated by a licensee depending on the type of analysis that is performed.

The compliance period may not go to peak dose. The waste that is disposed and where the waste is disposed will dictate when the peak dose may occur. For waste containing significant quantities of long-lived radionuclides the compliance period will be 10,000 years. The compliance period, in this case, will be followed by the performance period. The performance period will be as long as necessary to demonstrate that releases have been minimized to the extent reasonably achievable.

No changes were made to the guidance as a result of this comment.

F4.5 *Comment:* Martin Clauberg; Have you operationalized or defined what you mean by “long-lived radionuclides”? More importantly, what do you do with daughter products that probably or that might be more of an issue? Have you thought about defining that or putting some definitions on those considerations?

Response: Yes, the final rule provides a definition of long-lived radionuclides in §61.2 and considers daughter products.

> *Long-lived radionuclide* means radionuclides:
> (1) Where more than 10 percent of the initial activity of the radionuclide remains after 1,000 years,
> (2) Where the peak activity from progeny occurs after 1,000 years, or
> (3) where more than 10 percent of the peak activity of the radionuclide (including progeny) within 1,000 years remains after 1,000 years

This definition is also cited on Page 6-1, of NUREG-2175, footnote 1. Changes were made to the guidance, but not as a direct result of this comment.

F4.6 *Comment:* Betsy Forinash, page 61-62. I am concerned with the approach to the performance period with respect to the site-specific conditions that necessitate the analysis and the relationship to longer-lasting engineering barriers. Is the performance period approach a disincentive to robust engineered barriers?

Response: The performance period is now required primarily based on the type of waste that is disposed (i.e., for significant quantities of long-lived radionuclides) and the risks that they may pose. Delaying radiological impacts to the public for long periods of time is a very favorable outcome and should not be discouraged by the regulatory framework. The benefit to using robust engineered barriers or selecting favorable sites is that larger quantities and higher concentrations of waste may be safely disposed. The challenge of demonstrating long-term performance of engineered barriers is outweighed by the enhanced long-term performance that can be attained by utilizing robust engineered barriers. Requiring analyses into the performance period (e.g., beyond 10,000 years) is not intended to discourage the use of robust engineered barriers, but rather to demonstrate the long-term performance of those robust engineered barriers.

No changes were made to the guidance as a result of this comment.

F4.7 *Comment:* David Michlewicz, page 67. Isn’t inadvertent intrusion a form of common mode failure for subsequent exposure? Let’s say somebody drills a well there. They bring up some waste. They get exposed, but the well is there for others to use afterwards.

Response: NRC staff agrees with the commenter and has identified in Section 4.2 (formerly 4.3.1) that use of water from a well (i.e., as in the intruder-well and intruder-agriculture generic receptor scenarios) is considered acceptable for representing normal activities that the requirements in 10 CFR 61.13 specify that licensees must consider in an inadvertent intruder assessment

Changes were made to the guidance, but not as a direct result of this comment.

F4.8 *Comment:* John Greeves, page 67. How are people going to demonstrate defense-in-depth? I'm trying to figure out how are people going to demonstrate defense-in-depth? It's a lot of things, and you can point at them, but again defining whether that's demonstration of defense-in-depth is frankly in the eye of the beholder.

Response: The regulations at 10 CFR 61.12(o) requires licensees to identify defense-in-depth protections and describe the protections' capabilities, including a basis for each capability. Defense-in-depth for land disposal of radioactive waste means the use of multiple independent and, where possible, 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 to enhance the resiliency of the land disposal facility. NRC staff has provided guidance on acceptable approaches for identifying defense-in-depth protections, describing their capabilities, including a basis for each capabilities in Chapter 7.

No changes were made to the guidance as a result of this comment.

F4.9 *Comment:* Christina Brown, page 72. In terms of Class A waste not meeting the stability requirements, the Class A waste potentially containing DU which is long-lived, isn't that an issue if the DU waste has to meet the stability requirements?

Response: The new waste acceptance requirements apply to all operating land disposal facilities to ensure that waste acceptable for disposal provides reasonable assurance that the performance objectives will be met. In general, the use of the concentration limits specified in 10 CFR 61.55 remain protective of public health and safety; however, the concentration limits in 10 CFR 61.55 are designed to provide protection to an inadvertent intruder whose risk is typically bounded by the concentration of radionuclides in the waste. The limits were not intended to provide protection of the general population from releases, whose risk is typically affected by the total activity of certain radionuclides that tend to be more mobile in the environment and migrate off-site. Further, all existing land disposal facilities have taken varying amounts of waste containing long-lived radionuclides. The waste concentration limits in 10 CFR 61.55 may not be adequately protective for certain waste streams containing long-lived radionuclides that are classified as Class A by default because concentration limits were not developed (e.g., depleted uranium) for those long-lived radionuclides. Class A waste is considered relatively innocuous because it usually contains the types and quantities of radionuclides that will decay during the first 100 years and will present an acceptable hazard to an inadvertent intruder. Thus, regardless of the method proposed to develop allowable limits for specific radionuclides, a licensee must conduct technical analyses to demonstrate that the performance objectives will be met. NRC staff provides guidance on developing waste acceptance criteria in Chapter 7 (formerly Chapter 8) and conducting stability analyses in Chapter 5 of NUREG-2175.

No changes were made to the guidance as a result of this comment.

F.5 Other Comments

F.5.1 Barbara Warren comments (July 22, 2015, ML15208A102): Requests extension to submit comments until September 15, 2015.

Response: Comment period was extended as requested.

F5.2 through F5.4
Frank Marcinowski comments (July 23, 2015, ML15209A565)
Roger Seitz comments (July 24, 2015, ML15211A061)
Kent Rosenberger comments (July 24, 2015, ML15211A062)

Commenters requested an additional comment period on the draft NUREG-2175 (e.g., 120-day) after the final rule was issued and before NUREG-2175 became final guidance.

Response: The NRC generally tries to issue a draft guidance document concurrently with the proposed rule and a final guidance document concurrently with the final rule. In order for the rule to be implemented appropriately, the guidance needs to be available when the rule is issued. Although comments will not be specifically solicited on the final NUREG-2175, any comments received on the final guidance document will be considered if the guidance is revised in the future.

No changes were made to the guidance as a result of these comments.

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APPENDIX G
10 CFR PART 61 DEIS DEFAULT SCENARIOS

The NRC staff has developed a summary of the scenarios and calculations used to determine the waste classification concentrations specified in 10 CFR 61.55. The summary is intended to aid licensees and Agreement States in understanding how the waste classification concentration limits were developed. The NRC staff developed the concentration limits for the initial promulgation of 10 CFR Part 61 and their development is described in more detail in NUREG-0782 (See Vol. 2, Chapter 7 and Vol. 4, Appendix G; NRC, 1981a) and NUREG-0945 (NRC, 1982b). The calculations discussed in NUREG-0782 and summarized in this appendix include calculations to determine the waste classification limits as well as assess the potential impacts from the management of LLW and potential controls to ensure protection of public health and safety and the environment. To develop the waste classification limits in 10 CFR 61.55, the NRC staff relied upon a subset of the calculations and assumptions that are summarized in this appendix. Although this appendix summarizes calculations beyond those used to develop the waste classification limits, the NRC staff has indicated herein which approaches and parameter values were used specifically to develop the waste classification limits. In this appendix, the NRC staff summarizes the scenarios evaluated, assumptions employed, calculations performed, and adjustments made to develop the concentration limits.

After the initial promulgation of 10 CFR Part 61, NRC updated the impact analysis methodology in NUREG/CR-4370 (NRC, 1986a). The update principally included: (i) an update of the low-level radioactive waste source term, (ii) consideration of additional alternative disposal technologies, (iii) expansion of the methodology used to calculate disposal costs, (iv) consideration of an additional exposure pathway involving direct human contact with disposed waste due to a hypothetical drilling scenario, and (v) use of updated health physics analysis procedures (i.e., ICRP Publication 30 [ICRP; 1979, 1980, 1982]). The purpose of the update was, in part, to potentially be used as a methodology to generically analyze disposal of individual wastes that exceed Class C concentrations on a case-by-case basis. Therefore, the update to the impacts methodology did not alter the waste classification limits in 10 CFR 61.55 and are not summarized in this appendix.

<u>Overall Approach</u>

The NRC staff evaluated both acute and chronic exposures for a reference disposal facility to develop the 10 CFR 61.55 concentration limits. The NRC staff evaluated acute exposures using the intruder-construction receptor scenario and its variant, the intruder-discovery receptor scenario[1]. The NRC staff evaluated chronic exposures using the intruder-agriculture receptor scenario. Figures G-1 and G-2 depict the exposure pathways associated with the intruder-construction and intruder-agriculture scenarios, respectively. Both the acute and chronic receptor scenarios employed several common assumptions, including:

[1] For stable waste, the NRC staff assumed the intruder would recognize the waste and would limit exposures once the hazard was recognized. Thus, the NRC staff limited the number of hours of exposure for waste that is stable and segregated from unstable waste. This variant of the intruder-construction receptor scenario is known as the intruder-discovery receptor scenario.

- Temporary breakdown of institutional controls allowing inadvertent intrusion to occur
- Inadvertent intruder directly contacts the waste
- Intrusion into last disposal cell constructed (i.e., radionuclide decay during operations neglected)
- Waste remaining on the disposal site

To estimate exposures in each receptor scenario, the NRC staff evaluated common expressions of dose equivalent, *H*, using the following equation:

$$H = \sum_{i,j} PDCF \times C_a \qquad \text{(G.1)}$$

where

PDCF is the pathway dose conversion factor [Sv per Bq/m^3] for radionuclide *i* for exposure pathway *j*; and

C_a is concentration [Bq/m^3] of radionuclide *i* in environmental media (i.e., either onsite soil or air) at the inadvertent intruder access point for exposure pathway *j*.

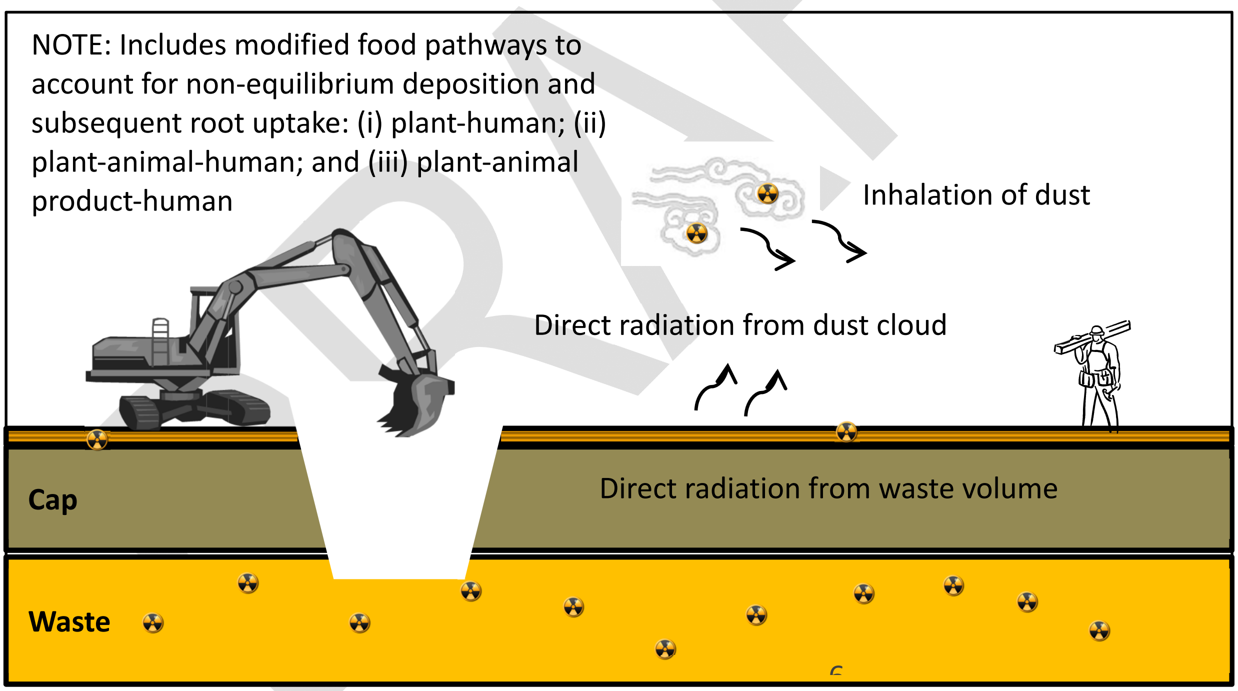

Figure G-1 Intruder-construction receptor scenario exposure pathways

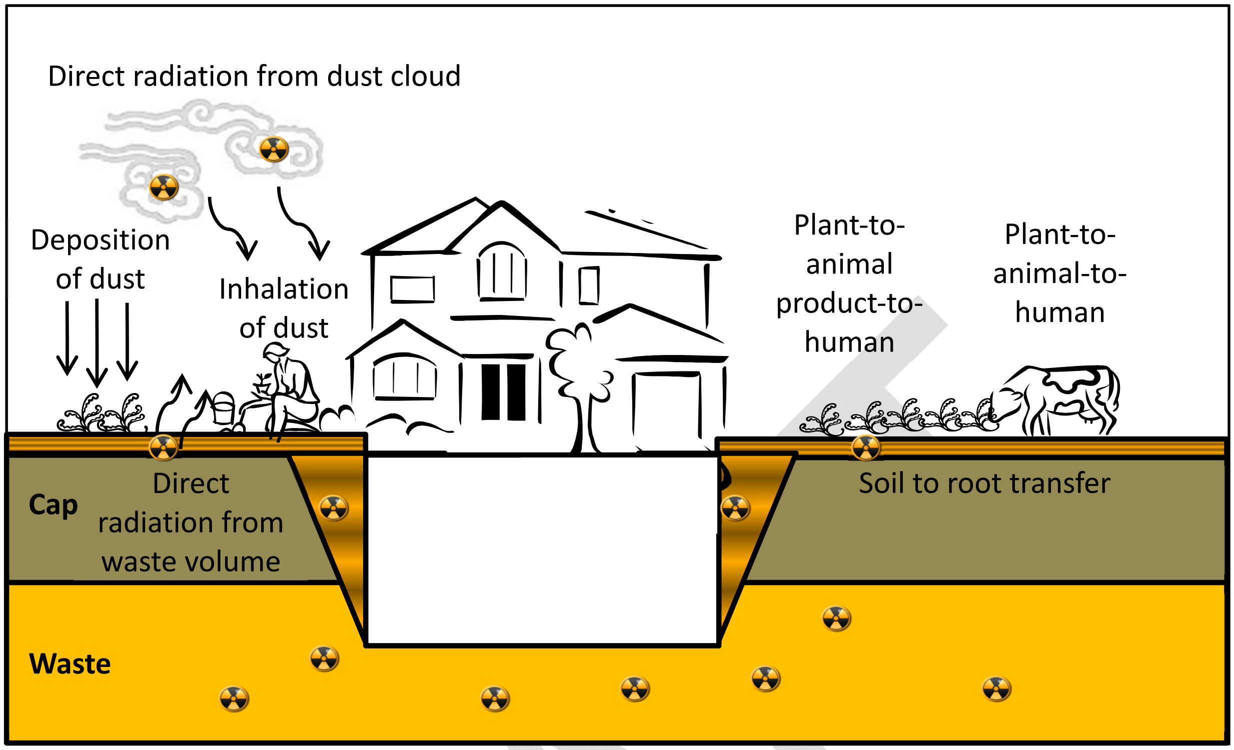

Figure G-2 Intruder-agriculture receptor scenario exposure pathways

The NRC staff reports the pathway dose conversion factors used in the calculations in Tables G.4 and G.7 of NUREG-0782 (NRC, 1981a) for the intruder-construction and intruder-discovery receptor scenarios. Pathway dose conversion factors used in the calculations for the intruder-agriculture receptor scenario are reported in Tables G.5 through G.7 of NUREG-0782 (NRC, 1981a). The pathway dose conversion factors were calculated in NUREG/CR-1759 (NRC, 1981b), Volume 3, Appendix B. The information used to calculate the pathway dose conversion factors includes human physiological parameters (e.g., breathing rates, nuclide metabolism), dietary intakes, and nuclide-specific food chain transfer rates. The dose for a particular uptake pathway (e.g., breathing contaminated air) at a specific site could be determined through the use of transfer factors (e.g., soil-to-air) and fundamental dose conversion factors. However, the NRC staff used pathway dose conversion factors that account for assumptions regarding environmental characteristics and human actions upon which the transfer factors would depend to determine, on a generic basis for a reference disposal site, the total organ doses received from any concentration of radionuclides in environmental media (e.g., air, water, soil).

Inhalation dose conversion factors were derived from Bates, et al. (1966) and ICRP Publication 19 (ICRP, 1972). Ingestion dose coversion factors were derived from RG 1.109, Rev. 1 (NRC, 1977a) and NUREG-0172 (NRC, 1977b). Direct gamma dose conversion factors for exposure to volumetric sources were calculated from equations in HASL-195 (1968) with emitted gamma energy characteristics in *Table of Isotopes,* 6th Ed. (Lederer et al., 1967). Direct gamma dose conversion factors for submersion in air were developed from NUREG-0456 (NRC, 1978).

The NRC staff estimated the concentration of radionuclides at the inadvertent intruder access point using a series of four factors to account for control mechanisms required by the regulation

that would result in differences between the concentration in the waste and the concentration to which the inadvertent intruder is actually exposed using the following equation:

$$C_a = C_w \times f_o \times f_d \times f_w \times f_s \quad \text{(G.2)}$$

where

C_w is the concentration [Bq/m^3] of radionuclide *i* in the waste and

f_o is the time-delay factor [unitless (-)], which accounts for all the control mechanisms that increase the time period between the cessation of operation of the reference disposal facility and the end of the active institutional control period for radionuclide *i*;

f_d is the site design and operation factor [-], which accounts for effects of any engineered barriers designed into the waste disposal facility in addition to any site operational practices that may reduce transport;

f_w is the waste form and package factor [-], which accounts for the physical and chemical characteristics of the waste that may inhibit release and transport of contaminants;

f_s is the site selection factor [-], which accounts for the dependence of the radionuclide concentration at the access point on either or both the environmental characteristics of the disposal site and/or exposure durations associated with the various receptor scenarios.

Additional description of the control factors and how the NRC staff estimated their values are provided below.

The NRC staff performed a screening analysis to determine which waste streams required special consideration with regard to institutional controls, waste form, and natural or engineered barriers. The process relied upon five distinct classification tests: regular standard, regular modified, layered standard, layered modified, and hot waste facility. Figure G-3 summarizes the classification test process.

For the regular standard classification test no additional control factors were applied to intruder-construction or intruder-agriculture scenarios. For the regular modified classification test, the NRC staff assumed that the waste is stable and segregated from unstable waste, thus only the intruder-discovery receptor scenario is applicable.

For the layered standard classification test, the NRC staff assumed that waste was likely to be disposed beneath a minimum of 2 meters of cover and 4 to 5 meters of other regular wastes, therefore, the intruder-agriculture receptor scenario was not applicable. Additional control factors apply to the intruder-construction scenario for air uptake and direct gamma exposures. For the layered modified classification test, the NRC staff assumed waste is stable and segregated from unstable waste, thus only the intruder-discovery scenario is applicable. The NRC staff also assumed no credit for layering of waste after 500 years in either the layered standard or layered modified classification tests.

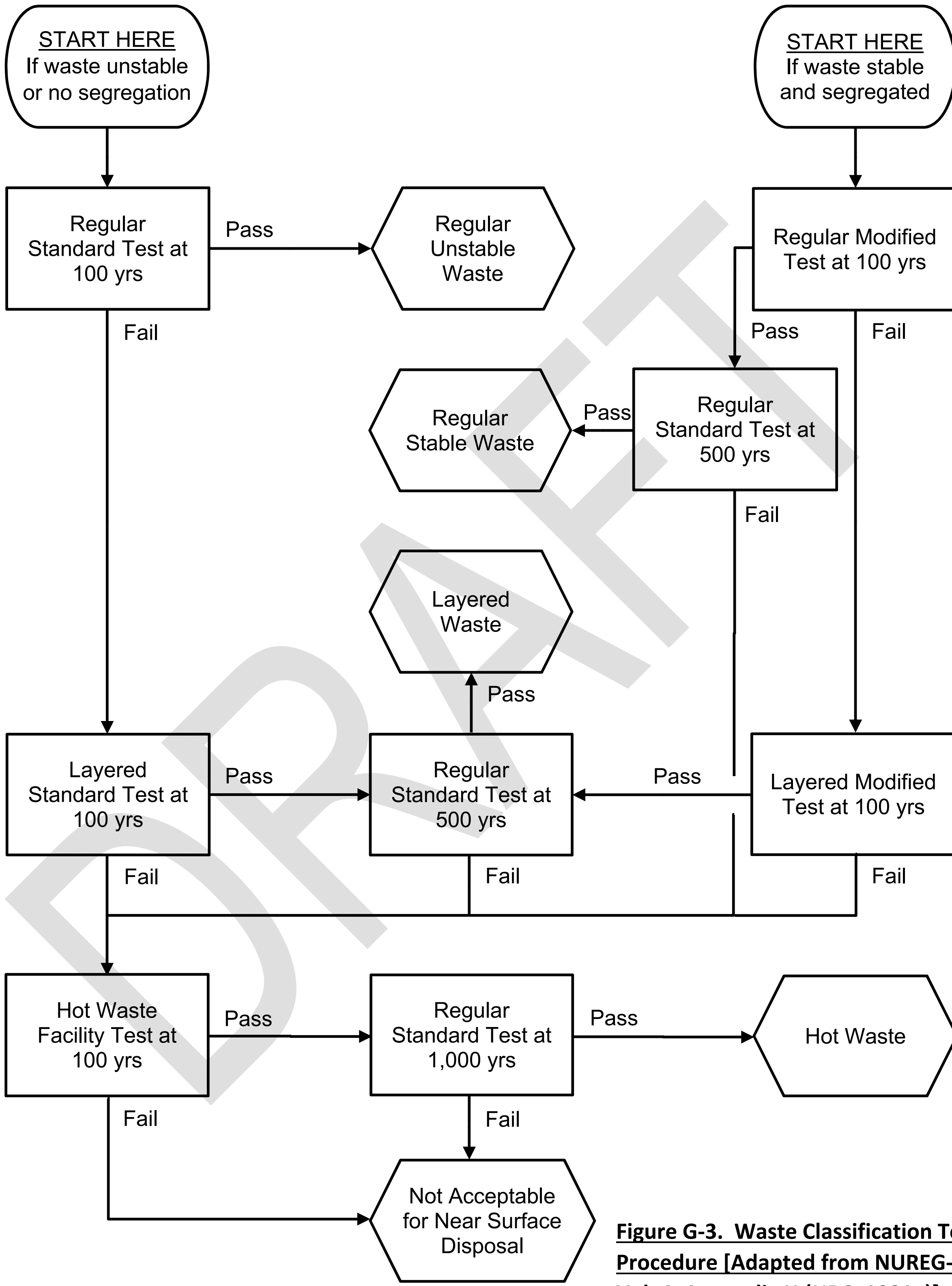

Figure G-3. Waste Classification Test Procedure [Adapted from NUREG-0782, Vol. 4, Appendix H (NRC, 1981a)]

For the hot waste facility classification test, the NRC staff assumed further controls for air uptake and direct gamma exposures in the intruder-construction scenario. The NRC staff assumed the intruder-agriculture scenario does not apply because of the design of the facility. The NRC staff also assumed no credit for controls associated with the hot waste facility after 1,000 years. Because the hot waste facility did not affect the concentration limits in 10 CFR 61.55, the control factors are not discussed further in this appendix.

In Chapter 7 of NUREG-0782 (NRC, 1981a), the NRC staff documents the calculation to derive concentration limits using a 500-mrem annual inadvertent intruder exposure. Table 7.1 of NUREG-0782 (NRC, 1981a) provides the concentration values calculated from the intruder-construction, intruder-discovery, and intruder-agriculture receptor scenarios. The NRC staff calculated the values in Table 7.1 assuming the most conservative assumption regarding the waste form (i.e., the waste form is dispersible as ordinary dirt and no credit is taken for improved waste forms). In other words, the values in Table 7.1 are derived using the regular standard and regular-modified classification tests described above at 100-years (for Class A and B limits) and the regular-standard classification test at 500-years (for Class C limits). The intruder-discovery receptor scenario at the end of the active institutional control period (i.e., 100 years) was originally considered as the basis for the Class B limit because NRC assumed that an intruder would recognize stabilized waste and limit exposures once the hazard was recognized. However, for several radionuclides, the intruder-discovery scenario at the end of the active institutional control period was less limiting than the proposed Class C limits, which were based on intruder-construction or intruder-agriculture receptor scenarios at 500 years. Thus, NRC decided not to establish a Class B limit for long-lived radionuclides. For short-lived radionuclides, the more limiting of either the Class C limit or the concentration established by the intruder-discovery scenario was selected by the NRC staff as the Class B limit.

After the scenario selection adjustment for Class B limits, two additional adjustments were made to the values listed in Table 7.1 of NUREG-0782 (NRC, 1981a). The first adjustment involved Cs-137. Section 7.2.5 of NUREG-0782 (NRC, 1981a) explains that waste contaminated with Cs-137 was likely to be diluted with waste with very low levels of Cs-137. Therefore, the NRC staff increased the limits for Cs-137 by a factor of 20 for Class A waste and a factor of 10 for Class B and C waste. Table 7.2 of NUREG-0782 (NRC, 1981a) lists these adjusted values and these Class A and B values were ultimately incorporated into Table 1 of 10 CFR 61.55. The second adjustment was the result of public comments on the initial proposed rule. The NRC staff received comments that further adjustments should be made to the Class C limits to account for the difficulty of an inadvertent intruder contacting Class C waste. The NRC staff agreed and increased all Class C values by a factor of 10, except for Cs-137, which had already been adjusted in NUREG-0782 (NRC, 1981a).

Time-Delay Factor

The NRC staff represented radioactive decay expected to occur over the time period between the cessation of operations at the reference disposal facility and the end of the active institutional control period. The NRC staff calculated a time delay factor, f_o, as follows:

$$f_o = e^{-\lambda t} \qquad \text{(G.3)}$$

where

λ is the radionuclide decay constant [yr^{-1}] of radionuclide *i* in the waste; and

t is the time [yr] from cessation of operations at the reference disposal facility to the time that the specific scenario is initiated.

The time-delay factor is a property of the scenario and the disposal technology being considered. For the intruder scenarios, the time-delay factor accounts for the time to the end of the active institutional control period (i.e., 100 years) for Class A and B limits or as long as the intruder barrier is assumed effective (i.e., 500 years) for the Class C limit. The assumed time period is equivalent to the assumption that the intrusion scenario involves the last disposal cell constructed at the site and neglects the possibility that the intrusion scenario may involve one of the earlier disposal cells.

Site Design and Operation Factor

The NRC staff estimated a site design and operation factor, f_d, to represent the impact of waste emplacement methods on the accessibility of waste to the inadvertent intruder. The site design and operation factor accounted for a number of considerations including the hazard of the waste, emplacement techniques, and exposure pathway. The site design and operation factor is dependent upon the efficiency of the disposal design and the receptor scenario. To develop values for the site design and operation factor, the NRC staff evaluated regular waste, which is emplaced without consideration of protecting an inadvertent intruder, and layered waste, which is emplaced at the bottom of the disposal cell, so that at least 5 meters of earth or other (lower activity) waste streams cover the layered waste. Within each waste type (i.e., regular and layered), the NRC staff assigned values denoting the dilution of the waste due to particular disposal practices regarding waste emplacement. The assumed values of the site design and operation factor for regular and layered wastes waste are listed in Table G-1.

Table G-1. Site Design and Operation Factors for Regular and Layered Waste

<table>
<tr><th rowspan="3">Emplacement Method†</th><th colspan="3">Intruder-Construction Receptor Scenario</th><th colspan="3">Intruder-Agriculture Receptor Scenario</th></tr>
<tr><th>Regular</th><th colspan="2">Layered‡</th><th>Regular</th><th colspan="2">Layered‡</th></tr>
<tr><th></th><th>Airborne Pathways</th><th>Direct Pathways§</th><th></th><th>Airborne Pathways</th><th>Direct Pathways§</th></tr>
<tr><td>Random Containers</td><td>0.5</td><td rowspan="3">0.1 × Regular Waste Value</td><td rowspan="3">(1/1200) × Regular Waste Value</td><td>0.5 × f_{mixing}§§</td><td rowspan="3">0.1 × Regular Waste Value</td><td rowspan="3">(1/1200) × Regular Waste Value</td></tr>
<tr><td>Stacked Containers</td><td>0.75</td><td>0.75 × f_{mixing}§§</td></tr>
<tr><td>Decontainerized</td><td>0.5</td><td>0.5 × f_{mixing}§§</td></tr>
<tr><td colspan="7">Notes:
† To derive the classification limits, the NRC staff only used a value for this factor that is consistent with random containers or decontainerized waste.
‡ The NRC staff used regular-standard and regular-modified classification tests to derive the classification limits. Therefore, the values for the layered classification tests reported in this table were not used to derive the classification limits.
§ Attenuation of radiation through a layer equivalent to 1 meter of soil.
§§ $f_{mixing} = \frac{Volume\ of\ Waste\ Excavated}{Total\ Volume\ of\ Excavation} = \frac{232\ m^3}{(232\ m^3 + 680\ m^3)} = 0.25$</td></tr>
</table>

Waste Form and Package Factor

The NRC staff estimated a waste form and package factor to represent the resistance of the waste to mobilization as a result of actions of the inadvertent intruder. For example, this factor would be considerably less than unity for waste streams solidified in a matrix and/or packaged in containers that are likely to retain their integrity at the time of the inadvertent intrusion. The waste form and package factor is dependent upon the property of the waste stream as it is being disposed. Therefore, the NRC staff assigned differing values for the various exposure pathways to account for the impact of the waste stream properties on mobilization in the exposure pathways.

To develop the values for the waste form and package factor, the NRC staff considered the accessibility of the contamination to mobilization, which is dependent on the waste form properties (e.g., surface contaminated objects versus activated metals) together with either the dispersibility of the contamination for airborne pathways or whether the waste was solidified (e.g., in cement) for direct exposure pathways. Thus, the NRC staff estimated the waste form and package factor, f_w, for airborne and direct exposure pathways according to the following equations:

$$f_w = f_{accessibility} \times f_{dispersibility} \quad \text{(Airborne Pathways)} \quad \text{(G.4a)}$$
$$f_w = f_{accessibility} \times f_{solidification} \quad \text{(Direct Pathways)} \quad \text{(G.4b)}$$

where

$f_{accessibility}$ is the accessibility mulitipler [unitless (-)] of each wasteform that accounts for the location of contamination in or on the waste;

DRAFT

$f_{dispersibility}$ is the dispersibility multiplier [-] for each wasteform that accounts for resistance to mobilization via air pathways; and

$f_{solidication}$ is the solidification multiplier [-] of each wasteform that accounts for self-shielding of direct radiation as a result of using a solidification agent.

The values of the accessibility, dispersibility, and solidification multipliers for the airborne and direct exposure pathways used to estimate the waste form and package factor are listed in Table G-2. For the purposes of developing waste classification limits, the NRC staff assumed no waste form credit for the dispersibility multiplier and no solidification credit for the solidification multipler to derive the classification limits. Therefore, the remaining values listed in Table G-2 were not used to develop the waste classification limits.

Table G-2. Accessibility, Dispersibility, and Solidification Multipliers for Airborne and Direct Exposure Pathways

	Airborne Exposure Pathways	Direct Exposure Pathways
Accessibility Multiplier		
Surface-contaminated waste and waste containing radionuclides in soluble form	1	1
Waste with significant metallic content, with both activated and surface crud contamination	0.1	0.1
Activated metals	0.01	0.1
Dispersibility Multiplier		
No waste form credit (i.e., soil)	1	N/A
Waste that crumbles or fractures extensively and decompose quickly	0.1	N/A
Mix of above and below wastes	0.01	N/A
Waste likely to resist biological and chemical attack with significant compressive strengths (e.g., good synthetic polymer)	0.001	N/A
Solidification Multiplier		
Wastes solidified using significant cement for solidification	N/A	0.8
Wastes without significant solidification	N/A	1

Notes:
The NRC staff assumed no waste form credit for the dispersibility multiplier and no solidification credit for the solidification multipler to derive the classification limits.

For food pathways evaluated in the intruder-agriculture receptor scenario, the NRC staff accounted for waste forms that would reduce leaching of radionuclides from disposed waste and subsequent uptake by plant roots. The NRC staff estimated the waste form and package factor, f_w, using the following equation for the food pathways:

$$f_w = M_o \times t_c \times f_{accessibility} \times f_{leaching} \qquad \text{(Food Pathways)} \qquad \text{(G.4c)}$$

where

M_o is the partition ratio [unitless (-)] of individual radionuclides between leachate and unsolidified waste forms;

t_c is the fraction of each year [-] that the waste is in contact with irrigation or rainwater;

$f_{accessibility}$ is the accessibility mulitipler [-] of each wasteform that accounts for the location of contamination in or on the waste; and

$f_{leaching}$ is the leaching multiplier [-] of each wasteform that accounts for reduction of leaching due to solidification and the presence or absence of chelating chemicals.

The values of the radionuclide-specific partition ratios are listed in Table G.14 of NUREG-0782, Vol. 4, Appendix G (NRC, 1981a). The irrigation contact time was assumed to be unity. The values for the accessibility multiplier values are identical to the values for airborne exposure pathways listed in Table G-2 above. The values for the leaching multiplier is a function of (i) a wasteform's resistance to leaching as a result of solidification technique, (ii) the presence of chelating agents or organic chemicals that may increase the mobility of radionuclides during and/or after leaching, and (iii) whether the waste containing chelating agents is mixed with other wastes or segregated when disposed. The values for the leaching multiplier for the food pathways used to estimate the waste form and package factor are listed in Table G-3. For the purposes of developing waste classification limits, the NRC staff assumed that waste is unsolidified. Therefore, the remaining values listed in Table G-3 were not used to develop the waste classification limits.

<u>Site Selection Factor</u>

The NRC staff estimated a site selection factor to represent the environmental characteristics of the site and/or the behavior of the inadvertent intruder. For direct exposure pathways, the the site selection factor is dependent upon the exposure duration and the areal extent of the direct gamma source (and its attenuation) that the inadvertent intruder is exposed to for the inadvertent intruder receptor scenario. For airborne exposure pathways, the site selection factor is dependent upon the transfer of contaminants in the soil to the air, which is a function of environmental characteristics of the region in which the disposal facility is located, and the exposure duration for the inadvertent intruder receptor scenario. For food exposure pathways, the site selection factor is dependent upon the amount of food consumed by the inadvertent intruder that is grown onsite. The NRC staff assumed that half the food consumed by the inadvertent intruder in the intruder-agriculture receptor scenario was grown onsite.

Table G-3. Leaching Multiplier Values for Food Exposure Pathways

	Waste contains or is disposed mixed with chelating agents or organic chemicals that may increase the mobility of radionuclides during and/or after leaching	Waste does not contain and is not disposed mixed with chelating agents or organic chemicals that may increase the mobility of radionuclides during and/or after leaching
Unsolidified waste	1	1
Waste solidified to a level of performance assuming: • half of waste is solidified using cement and • half is solidified using urea-formaldehyde	1	1/4
Waste solidified to a level of performance assuming: • half of waste is solidified using cement and • half is solidified using synthetic organic polymers	1/4	1/16
Waste solidified to a level of performance assumingall waste is solidified using synthetic organic polymers	1/16	1/64
Notes: The NRC staff assumed waste is unsolidified to derive the classification limits.		

The site selection factor, f_s, for direct pathways was estimated by the following equation for the intruder-construction and intruder-agriculture scenario:

$$f_s = \sum_k f_{attenuation} \times \ t_k \qquad \text{(G.5)}$$

where

$f_{attenuation}$ is the attenuation factor [unitless (-)] for activity *k* and

t_k is the fraction [-] of the year that the inadvertent intruder engages in activity *k*.

The NRC staff estimated the value of the site selection factors for the direct pathways using the values listed for the parameters in Table G-4. The site selection factor, f_s, for airborne pathways was estimated by the following equations for the intruder-construction and intruder-agriculture scenarios, respectively:

$$f_s = T \times t_k \qquad \text{(Intruder-Construction)} \qquad \text{(G.6a)}$$

$$f_s = T \times \sum_k \left[\frac{m_k}{m_g} \times t_k\right] \qquad \text{(Intruder-Agriculture)} \qquad \text{(G.6b)}$$

where

T is the transfer factor [m^3(air)/m^3(soil)] of contaminants from soil to air;

m_k is the mass loading [µg/m^3] of particulates in air during activity *k*;

m_g is the mass loading [µg/m^3] of particulates in air while gardening; and

t_k is the fraction [unitless (-)] of the year that the inadvertent intruder engages in activity *k*.

The NRC staff estimated the value of the site selection factors for the airborne pathways using the values listed for the parameters in Table G-4.

DRAFT

Table G-4. Soil-to-Air Transfer Factors, Annual Activity Fractions, and Attenuation Factors for the Direct and Airbone Exposure Pathways

	Intruder-Construction Receptor Scenario	Intruder-Agriculture Receptor Scenario		
Soil-to-Air Transfer Factor	3.53×10^{-10} m^3/m^3†	2.53×10^{-10} m^3/m^3		
Activity	**Time**	**Mass Loading**	**Time**	**Attenuation Factor§**
Construction	$\frac{500\ hrs}{8760\ hrs}$	N/A		1
Discovery‡	$\frac{6\ hrs}{8760\ hrs}$	N/A		1
Gardening	N/A	565 µg/m^3	$\frac{100\ hrs}{8760\ hrs}$	0.74
Outdoor	N/A	100 µg/m^3	$\frac{1700\ hrs}{8760\ hrs}$	0.74
Indoor	N/A	50 µg/m^3	$\frac{4380\ hrs}{8760\ hrs}$	0.24
Offsite	N/A	0 µg/m^3	$\frac{2580\ hrs}{8760\ hrs}$	0

NOTES:

† The NRC staff estimated the soil-to-air transfer factor for the intruder-construction receptor scenario by accounting for environmental characteristics of the site using the equation, $T = T_o \times \left(\frac{10}{v}\right) \times \left(\frac{s}{30}\right) \times \left(\frac{50}{PE}\right)^2$, where T_o is equal to 2.53×10^{-10} [see NUREG-1759, Vol. 3 (NRC, 1981b)], v is the average wind speed at the site in m/s (v = 3.61 m/s), s is the silt content of the site soils in percent (s = 50%), and PE is the Thornthwaite precipitation-evaporation index of the site vicinity indicative of the antecedent moisture conditions (PE = 91).

‡ For stable waste, the NRC staff assumed the intruder would recognize the waste and would limit exposures once the hazard was recognized. Thus, the NRC staff limited the number of hours of exposure for waste that is stable and segregated from unstable waste. This variant of the intruder-construction receptor scenario is known as the intruder-discovery receptor scenario.

§ The NRC staff only considered attenuation of direct radiation in the intruder-agriculture receptor scenario, thus the values for the intruder-construction receptor scenarios are presented as unity (i.e., no attenuation) in this table. The NRC staff estimated the attenuation of direct radiation in the intruder-agriculture receptor scenario assuming the source's areal extent is a circular disc using the equation, $f_{attenuation} = \frac{E(\mu \times r_1) - E(\mu \times r_2)}{E(\mu \times r_0)}$, where E(µ×r) is the first-order exponential integral; µ is the linear attenuation coefficient (µ = 0.0097 m^{-1}); and r_0, r_1, and r_2 are the radii of the circular disc geometry shown in NUREG-0782, Figure G.5. For the time spent outdoors, r_1 in the above equation equates to r_0 in NUREG-0782, Figure G.5, (NRC, 1981a) because no attenuation by structures is assumed. For time spent indoors, r_1 accounts for the attenuation afforded by the house.

DRAFT

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