



NUREG-2175

Guidance for Conducting Technical Analyses for 10 CFR Part 61

Draft Report for Comment

Office of Nuclear Material Safety and Safeguards

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Guidance for Conducting Technical Analyses for 10 CFR Part 61

Draft Report for Comment

Manuscript Completed: January 2015
Date Published: March 2015

Prepared by:

D. Esh, C. Grossman, H. Arlt, C. Barr, P. Yadav

Office of Nuclear Material Safety and Safeguards

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For any questions about the material in this report, please contact: Priya Yadav, Project Manager, at 301-415-6667 or by e-mail at Priya.Yadav@nrc.gov.

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ABSTRACT

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

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

PREFACE

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

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

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

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

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

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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.

ACRONYMS AND ABBREVIATIONS

ACAP	Alternative Cover Assessment Project
ADAMS	Agencywide Documents Access and Management System
ALARA	as low as reasonably achievable
ASTM	American Society for Testing and Materials
BTP	branch technical position
BTP CA	BTP on concentration averaging and encapsulation
CFR	<i>Code of Federal Regulations</i>
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	<i>Federal Register</i>
GIS	Geographic Information Systems
HLW	high-level waste
ICRP	International Commission on Radiological Protection
IMPEP	Integrated Materials Performance Evaluation Program
K_d	distribution coefficient
LLW	low-level radioactive waste
m	meter
mm	millimeter
mrem	millirem
mSv	millisievert
nCi/g	nanocuries per gram
NCRP	National Council on Radiation Protection and Measurements
NPV	net present value
NRC	U.S. Nuclear Regulatory Commission
OMB	Office of Management and Budget
PA	performance assessment
PAP	protective assurance period
PMF	probable maximum flood
PMP	probable maximum precipitation
PRA	probabilistic risk assessment
SOF	sum of fractions
QA	quality assurance
QA/QC	quality assurance/quality control
USGS	U.S. Geological Survey
yr	year

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

1.0 INTRODUCTION

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

1.1 Background

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

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

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

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

1.1.1 Performance Objectives

The performance objectives for a LLW disposal facility are contained in 10 CFR Part 61, Subpart C. The general requirement in 10 CFR 61.40 notes that land disposal facilities must be

1 sited, designed, operated, closed, and controlled after closure so that reasonable assurance
2 exists that exposures to humans are within the limits established in the performance objectives
3 in 10 CFR 61.41 through 10 CFR 61.44. During and after facility operations, the performance
4 objective at 10 CFR 61.41 requires the protection of the general population from releases of
5 radioactivity.

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

17
18 The performance objective in 10 CFR 61.42 requires that the disposal facility must protect the
19 *inadvertent intruder* at all times during the compliance period after active institutional controls
20 are removed (i.e., 100 years after facility closure).

- 21 • The performance objective 10 CFR 61.42(a) provides an annual dose limit of 5 mSv
22 (500 mrem) for the compliance period.
- 23 • The performance objective in 10 CFR 61.42(b) requires that design, operation, and
24 closure of the *land disposal facility* shall minimize exposures to any inadvertent intruder
25 into the disposal site at any time during the protective assurance period and that the
26 annual dose shall be below 5 mSv (500 mrem) or a level that is supported as reasonably
27 achievable based on technological and economic considerations.
- 28 • The performance objective in 10 CFR 61.42(c) requires exposures to the inadvertent
29 intruder at any time during the performance period to be minimized to the extent
30 reasonably achievable.

31
32 Sections 10 CFR 61.41 and 10 CFR 61.42 require a demonstration of protection beyond closure
33 of the disposal facility. The length of time that these requirements specify is defined in
34 10 CFR 61.2, "Definitions". Specifically:

35 *Compliance period* is the time out to 1,000 years after closure of the disposal facility.

36
37 *Protective assurance period* is the period from the end of the compliance period through
38 10,000 years following closure of the site.

39
40 *Performance period* is the timeframe established for considering waste and site
41 characteristics to evaluate the performance of the site after the protective assurance
42 period.

43
44 The performance objective in 10 CFR 61.43 requires protection of individuals during operations.
45 Compliance with 10 CFR 61.43 is determined largely through compliance with the standards for
46 radiation protection set forth in 10 CFR Part 20, and therefore, is not discussed further in this
47 document.

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

7 **1.1.2 Safety Case**

8
9 Section 10 CFR 61.2 defines a *safety case* as a collection of information that demonstrates the
10 assessment of the safety of a waste disposal facility. This includes the technical analyses
11 discussed in Section 1.1.4, as well as information on defense-in-depth and supporting evidence
12 and reasoning on the strength and reliability of the technical analyses and the assumptions
13 made therein. The safety case also includes description of the safety relevant aspects of the
14 site, the design of the facility, and the managerial control measures and regulatory controls.
15

16 A safety case for a land disposal facility covers the suitability of the site and the design,
17 construction and operation of the facility, the assessment of radiation risks and assurance of the
18 adequacy and quality of all of the safety related work associated with the disposal facility. The
19 purpose of a safety case is to provide a sufficient level of detail regarding the description of all
20 safety relevant aspects of the site, the design of the facility, and the managerial control
21 measures and regulatory controls to inform the decision whether to grant a license for the
22 disposal of LLW and provide the public assurance that the facility will be designed, constructed,
23 operated, and closed safely (IAEA, 2012).
24

25 Licensing decisions are based on whether there is reasonable assurance that the performance
26 objectives can be met. Defense-in-depth protections, such as siting, wasteforms, radiological
27 source-term, engineered features, and natural system features of the disposal site, combined
28 with technical analyses and scientific judgment form the safety case for licensing a LLW
29 disposal facility. The insights derived from technical analyses include supporting evidence and
30 reasoning on the strength and reliability of the layers of defense relied upon in the safety case.
31 These insights provide input for making regulatory decisions. The safety case must conclude
32 that public health and safety will be adequately protected from the disposal of LLW (including
33 long-lived LLW). A clear case for the safety of a disposal facility also serves to enhance the
34 communication among stakeholders.
35

36 Finally, the NRC staff envisions that the safety case for a land disposal facility would evolve
37 over time as new information is gained during the various phases of the facility's development
38 and operation. Therefore, the NRC staff expects that the safety case will be updated as new
39 information that could significantly impact safety of the facility is learned. Section
40 10 CFR 61.28(a) requires that the application for closure of a licensed land disposal facility must
41 include a final revision to the safety case.

42 **1.1.3 Defense-in-Depth Analyses**

43
44 Section 10 CFR 61.2 defines defense-in-depth as the use of multiple independent and
45 redundant layers of defense such that no single layer, no matter how robust, is exclusively relied
46 upon. Defense-in-depth for a land disposal facility includes, but is not limited to, the use of
47 siting, wasteforms and radionuclide content, engineered features, and natural geologic features

1 of the disposal site. Section 8.0 describes the information that a licensee should provide and a
2 *reviewer* should evaluate with respect to the technical analyses for demonstrating that a land
3 disposal facility incorporates defense-in-depth protections during the operational and post-
4 closure phases of the land disposal facility lifecycle. Section 10 CFR 61.13(f) requires licensees
5 to complete analyses that demonstrate the proposed disposal facility includes defense-in-depth
6 protections.

7 **1.1.4 Technical Analyses**

8
9 The technical analyses needed to demonstrate that the performance objectives of Subpart C
10 are met are provided in 10 CFR 61.13(a) through (f). Technical analyses assess the impact of
11 site-specific factors on the performance of the disposal facility and the site environment both (1)
12 during the operational period, as in the analysis for protection of individuals during operations,
13 and (2) for disposal of radioactive waste over the longer term, as in the analyses for protection
14 of the general population from releases of radioactivity, protection of inadvertent intruders,
15 stability of the disposal site after closure, and assessment of long-term impacts from LLW
16 disposal over the protective assurance and performance periods.

17
18 In this document, the term “technical analyses” comprises the *performance assessment*,
19 *intruder assessment*, *site stability analysis*, *defense-in-depth* analyses, protective assurance
20 period analyses, and *performance period analyses*. A description of each of the analyses is
21 presented in the following sections.

22 **1.1.4.1 Performance Assessment**

23
24 A performance assessment (PA) is a type of *risk* analysis that addresses (1) what can happen,
25 (2) how likely it is to happen, and (3) what are the resulting impacts (Eisenberg et al, 1999).
26 These impacts can then be compared to the performance objective in 10 CFR 61.41
27 (radiological protection of the general public). The requirements for a performance assessment
28 are set forth in 10 CFR 61.13(a). A performance assessment shall:

- 29 (1) Consider features, *events*, and processes (*FEPs*) that might affect demonstration of
30 compliance with 10 CFR 61.41. The FEPs considered must represent a range of
31 phenomena with both beneficial and adverse effects on performance, and must consider
32 the specific technical information required in 10 CFR 61.12(a) through 10 CFR 61.12(i).
33 A technical basis for inclusion or exclusion of specific FEPs must be provided.
- 34 (2) Evaluate specific FEPs if their omission would significantly affect meeting the
35 performance objective specified in 10 CFR 61.41.
- 36 (3) Consider the likelihood of disruptive or other unlikely FEPs for comparison with the limits
37 set forth in 10 CFR 61.41.
- 38 (4) Reflect new FEPs different from the compliance period that address significant
39 uncertainties inherent in the long timeframes associated with demonstrating compliance
40 with 10 CFR 61.41(b) only if scientific information compelling such changes is available.
- 41 (5) Provide a technical basis for either inclusion or exclusion of *degradation*, deterioration,
42 or alteration processes (e.g., of the *engineered barriers*, wasteform, site characteristics)
43 and interactions between the disposal facility and site characteristics that might affect
44 meeting the performance objective in 10 CFR 61.41.

- 1 (6) Provide a technical basis for *models* used in the performance assessment such as
2 comparisons made with outputs of detailed process-level models or empirical
3 observations (e.g., laboratory testing, field investigations, and natural analogs).
- 4 (7) Evaluate *pathways* including air, soil, groundwater, surface water, plant uptake, and
5 exhumation by burrowing animals.
- 6 (8) Account for uncertainties and variability in the projected behavior of the disposal system
7 (e.g., disposal facility, natural system, and environment).
- 8 (9) Consider *alternative conceptual models* of *features* and *processes* that are consistent
9 with available data and current scientific understanding, and evaluate the effects that
10 alternative conceptual models have on the understanding of the performance of the
11 disposal facility.
- 12 (10) Identify and differentiate between the roles performed by the natural disposal site
13 characteristics and design features of the disposal facility in limiting releases of
14 radioactivity to the general population.

15 **1.1.4.2 Inadvertent Intrusion Assessment**

16
17 The 10 CFR Part 61 regulations envision a period of active institutional controls for 100 years
18 following closure of the LLW disposal facility. During that time period, the disposal site and its
19 contents are protected from disturbance by potential intruders through a series of measures
20 (e.g., site access controls). At the end of the 100 years of active institutional controls,
21 10 CFR Part 61 requires licensees to assume there will be no active caretaking of the disposal
22 site and it is possible for inadvertent intruders to gain access. An inadvertent intruder is defined
23 in 10 CFR 61.2, "Definitions," as "a person who might occupy the disposal site after closure and
24 engage in normal activities, such as agriculture, dwelling construction, resource exploration or
25 exploitation (e.g., well drilling) or other reasonably foreseeable pursuits that might unknowingly
26 expose the person to radiation from the waste included in or generated from a disposal facility."
27 Licensees should demonstrate that potential inadvertent intruders, who might occupy the site at
28 any time after institutional controls over the disposal site are removed, will be protected.

29
30 An inadvertent intrusion assessment (also referred to as an "intruder assessment") is an
31 iterative process involving site-specific, prospective modeling evaluations of potential
32 radiological consequences as a result of reasonably foreseeable human activities that might
33 unknowingly occur should an individual occupy a near-surface facility for disposal of LLW after
34 the loss of institutional controls. The intruder assessment is used to evaluate how these
35 impacts compare to the performance objective in 10 CFR 61.42.

36
37 Because there is no scientific basis for quantitatively predicting the probability of a future
38 disruptive human activity over long timeframes, an inadvertent intruder assessment does not
39 consider the probability of inadvertent intrusion occurring. Rather, the assessment assumes
40 that reasonably bounding *receptor scenarios* occur and evaluates the radiological
41 consequences that could be experienced by inadvertent intruders should institutional controls or
42 societal memory be lost (NCRP, 2005).

43 As stated in 10 CFR 61.13(b), analyses of the protection of inadvertent intruders must
44 demonstrate there is reasonable assurance the *waste acceptance criteria* developed in
45 accordance with 10 CFR 61.58 will be met, adequate barriers to inadvertent intrusion will be
46 provided, and any inadvertent intruder will not be exposed to doses that exceed the limits set

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

- 3 (1) Assume that an inadvertent intruder occupies the disposal site at any time during the
4 compliance period (i.e., 1,000 years) after the period of institutional controls ends, and
5 engages in normal activities including agriculture, dwelling construction, resource
6 exploration or exploitation (e.g., well drilling), or other reasonably foreseeable pursuits
7 that are consistent with activities in and around the site at the time of closure and that
8 unknowingly expose the intruder to radiation from the waste.
- 9 (2) Identify adequate barriers to inadvertent intrusion that inhibit contact with the waste or
10 limit exposure to radiation from the waste, and provide a basis for the time period over
11 which barriers are effective.
- 12 (3) Account for uncertainties and variability.

13 **1.1.4.3 Site Stability Analysis**

14
15 The site stability analysis evaluates the long-term stability of the disposal site and can be used
16 by a licensee to determine compliance with 10 CFR 61.44 (see Section 5.0). The specific
17 requirements for the analyses are set forth in 10 CFR 61.13(d):

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

25 **1.1.4.4 Protective Assurance Period Analyses**

26
27 The primary purpose of the protective assurance period analyses is to provide information that
28 demonstrates that releases of radioactivity from a LLW disposal facility are minimized during the
29 protective assurance period, which is the period from the end of the compliance period through
30 10,000 years following closure of the site. Minimization is the reduction of doses to as low as
31 reasonably practical with technical and economic factors taken into consideration. The
32 performance objectives in 10 CFR 61.41(b) and 10 CFR 61.42(b) require that the annual dose
33 shall be below 5 mSv (500 mrem) or a level that is supported as reasonably achievable based
34 on technological and economic considerations for (1) concentrations of radioactive material that
35 may be released to the general environment, and for (2) exposures to any inadvertent intruder,
36 respectively. Section 6.0 provides guidance on developing the technical analyses for the
37 protective assurance period.

38 **1.1.4.5 Performance Period Analyses**

39
40 The primary purpose of the performance period analyses is to provide information to decision-
41 makers with respect to the potential performance of the disposal site for the disposal of
42 *long-lived waste*. Licensees should conduct performance period analyses for the period after
43 the 10,000 year (yr) protective assurance period. Performance period analyses are not required
44 if the disposal facility is not accepting sufficient quantities of long-lived waste. Section 7.0

1 provides guidance on how to determine if performance period analyses are necessary. The
2 performance period analyses are only required for disposal sites with waste that contains
3 radionuclides with average concentrations exceeding the values specified in Table A of
4 10 CFR 61.13(e), or if necessitated by site-specific conditions. The performance period
5 analyses required at 10 CFR 61.13(e) shall:

- 6 (1) Assess how the disposal site limits the potential long-term radiological impacts,
7 consistent with available data and current scientific understanding.
- 8 (2) Identify and describe the features of the design and site characteristics that will
9 demonstrate that the performance objectives set forth in 10 CFR 61.41(c) and
10 10 CFR 61.42(c) will be met.

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

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

21
22 Both the performance assessment and intruder assessment are evaluated over all three
23 timeframes, however, the stability analyses are only applied to the compliance period and
24 protective assurance period. Defense-in-depth is applicable over all three time periods and all
25 three analysis types. All of the information contributes to the demonstration that the Subpart C
26 performance objectives are met.

27 **1.1.5 Waste Acceptance Requirements**

28
29 Requirements for waste acceptance are specified in 10 CFR 61.58, "Waste Acceptance". The
30 regulations require licensees to identify (1) criteria for the acceptance of waste for disposal (i.e.,
31 waste acceptance criteria), (2) acceptable methods for characterizing the waste, and (3) a
32 program to certify that waste meets the acceptance criteria prior to transfer to the disposal
33 facility. The waste acceptance requirements are intended to provide reasonable assurance that
34 the performance objectives of Subpart C will be met.

35
36 The waste acceptance criteria, as specified in 10 CFR 61.58(a) must identify allowable activities
37 and concentrations of specific radionuclides, acceptable wasteform characteristics and
38 container specifications, and restrictions or prohibitions on waste, materials, or containers that
39 might affect meeting the performance objectives. The criteria for allowable activities and
40 concentrations of specific radionuclides must be developed from either the technical analyses
41 required by 10 CFR 61.13 for any land disposal facility or the waste classification requirements
42 set forth in 10 CFR 61.55 for a near-surface disposal facility.

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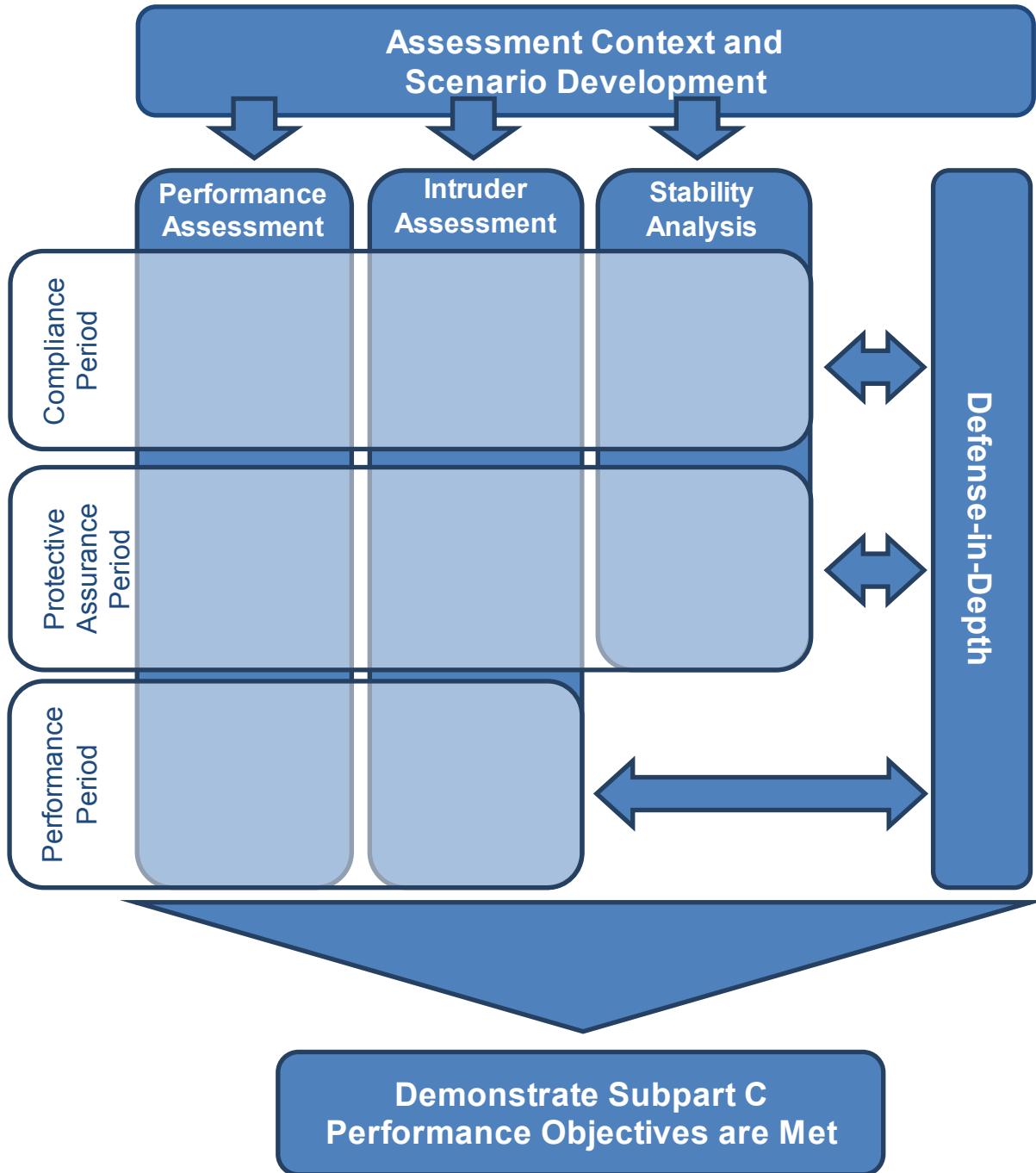


Figure 1-1 Technical Analyses Relationship to Analyses Timeframes and Performance Objectives

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

8
9 10 CFR 61.58(c) requires a program to certify that waste meets the acceptance criteria prior to
10 shipment to the disposal facility. Certification of waste provides assurance that a disposal
11 facility operates within the limits established to demonstrate compliance with the performance
12 objectives of Subpart C. The certification program must:

- 13 (1) Designate authority to certify and receive waste for disposal.
- 14 (2) Provide procedures for certifying that waste meets the waste acceptance criteria.
- 15 (3) Specify documentation required for waste characterization, shipment, and certification.
- 16 (4) Identify records, reports, tests, and inspections that are necessary.
- 17 (5) Provide approaches for managing waste to maintain its certification status.

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

21 **1.1.6 Agreement State Interactions**

22
23 Agreement State regulators may request technical assistance from the NRC staff to conduct
24 reviews of the technical analyses listed above and also to assist in interpreting the guidance in
25 this document. NRC provides three types of technical assistance to Agreement States: routine,
26 special, and programmatic (NRC, 2013).

27
28 Routine technical assistance is provided as part of NRC's daily interaction with Agreement
29 States. This assistance may include, but is not limited to, the discussion of technical issues
30 regarding licensing, compliance, and security. Examples of routine technical assistance include
31 requests for and the sharing of information on licensing, inspection, security, and enforcement
32 activities. The NRC staff may perform confirmatory reviews of portions of completed Agreement
33 State technical assessments, on a case-by-case basis, when resources are available.

34
35 Special technical assistance may require specific assignment of the NRC staff or consultants for
36 a specified period and for a specific job. An Agreement State may not have the special
37 technical expertise that is required to address a particular need, or an Agreement State may
38 experience a temporary constraint on resources. Consequently, an Agreement State may
39 request direct special technical assistance from NRC that would involve NRC licensing and
40 inspection staff conducting independent licensing. Direct technical assistance to an Agreement
41 State in these circumstances will be conducted on a case-by-case basis when NRC believes
42 that such assistance is necessary. The provision of such assistance will be based on the
43 availability of staff resources and any assistance will be cost-reimbursable.

44

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

5 **1.2 Purpose of This Guidance Document**

6
7 This guidance document is intended to support the implementation of the requirements for
8 technical analyses and waste acceptance to demonstrate compliance with the 10 CFR Part 61
9 performance objectives.

10 **1.2.1 Relationship to Other NRC Guidance**

11
12 The NRC staff has issued several guidance documents to assist in the implementation of the
13 requirements of 10 CFR Part 61. Additionally, in certain cases, guidance for other NRC
14 regulatory programs (e.g., NUREG-1757) may be adapted to 10 CFR Part 61. Early guidance
15 for the implementation of 10 CFR Part 61 (e.g., NUREG-1199 and NUREG-1200) was generally
16 prescriptive. More recently, review of site-specific performance assessments has become more
17 performance-based, driven in part by the Commission’s 1995 probabilistic risk assessment
18 (PRA) policy statement (NRC, 1995a). More recent guidance (e.g., NUREG-1573 and
19 NUREG-1854) has been developed that might be helpful for completing or reviewing a
20 performance assessment. The following documents, among others provided in Section 11.0 of
21 this document, are available to 10 CFR Part 61 licensees and reviewers for guidance:
22

- 23 (1) NUREG-1200, Revision 3, “Standard Review Plan for the Review of a License
24 Application for a Low-Level Radioactive Waste Disposal Facility,” issued April 1994,
25 provides regulators with procedures and guidance for reviewing license applications for
26 new disposal facilities (NRC, 1994). NUREG-1200 identifies areas of review and review
27 procedures for evaluating technical analyses, including what is referred to today as a
28 performance assessment (NRC, 1994). NUREG-1200 was developed using a
29 regulatory approach that was generally prescriptive.
30
- 31 (2) NUREG-1573, “A Performance Assessment Methodology for Low-Level Radioactive
32 Waste Disposal Facilities” was issued in October 2000 to assist licensees in performing
33 performance assessments to comply with 10 CFR 61.41 (NRC, 2000a) and is
34 referenced throughout this document. NUREG-1573 developed a bibliography of
35 technical references applicable to LLW disposal (as of 2000) in its Appendices B and C.
36 NUREG-1573 provides guidance on an acceptable approach for systematically
37 integrating *site characterization*, facility design, and performance modeling into a single
38 performance assessment process for purposes of demonstrating compliance with
39 10 CFR 61.41. The guidance in NUREG-1573 might help ensure the consistency of
40 different reviews.
41

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

1 Part 61 has changed since NUREG-1573 was developed in 2000 (see Appendix A). In
2 addition, different types of wastes (e.g., larger quantities of long-lived waste) are being
3 considered for disposal. Therefore, this guidance also supplements the guidance in
4 NUREG-1573.
5

6 (3) NUREG-1854, "NRC Staff Guidance for Activities Related to U.S. Department of Energy
7 Waste Determinations," issued August 2007, provides guidance specific to the NRC
8 staff's review of technical analyses for DOE waste determinations (NRC, 2007a). DOE
9 uses technical analyses that are documented in a "waste determination" to evaluate
10 whether the waste at four sites in the States of South Carolina, Idaho, Washington, and
11 New York, is high-level waste (HLW) or *waste incidental to reprocessing* (incidental
12 waste). A waste determination is DOE's analysis of whether the waste will meet the
13 applicable criteria to be classified as incidental waste. The four DOE sites are operating
14 under different requirements for waste evaluation and management; however, they all
15 include criteria that specifies the waste will be disposed of in compliance with, or with
16 comparable safety requirements to, the performance objectives in 10 CFR Part 61,
17 Subpart C. NUREG-1854 contains information that can also be used for conducting the
18 technical analyses referred to in this document.
19

20 (4) "Final Branch Technical Position on Concentration Averaging and Encapsulation,
21 Revision in Part to Waste Classification Technical Position," dated January 17, 1995
22 (NRC, 1995b), defines a subset of concentration averaging and encapsulation practices
23 that the NRC staff finds acceptable in determining the concentrations of the
24 radionuclides tabulated in 10 CFR 61.55, "Waste Classification." Although this branch
25 technical position (BTP) is more intended to aid LLW generators in determining
26 wasteform concentrations, it may prove useful to LLW disposal facility operators in
27 determining site-specific waste acceptance criteria (see Section 9.0). The NRC staff
28 updated this BTP and issued "Draft Branch Technical Position on Concentration
29 Averaging and Encapsulation, Revision 1" in May 2012 that revised the NRC staff
30 positions in the 1995 version (NRC, 2012a). The NRC staff expects to complete the final
31 version of this BTP by the end of 2014.
32

33 (5) NUREG-1757, "Consolidated NMSS Decommissioning Guidance: Characterization,
34 Survey, and Determination of Radiological Criteria," dated September 30, 2006, provides
35 guidance on the evaluation of engineered barriers used in site decommissioning (NRC,
36 2006). If similar engineered barriers are used in land disposal of LLW, then this
37 guidance might be useful to a licensee.
38

39 The purpose of this guidance document is to complement the aforementioned documents and
40 provide guidance in areas not previously covered. The NRC staff has attempted to provide
41 references to other guidance documents that may be useful for specific topics. Section 11.0 of
42 this document contains a road map directing the reader to individual sections of the documents
43 above, as well as to other guidance documents that might be useful to 10 CFR Part 61
44 licensees and reviewers.
45
46

1 **1.2.2 What is New in this Document?**
2

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

- 6 (1) Acceptable approaches to identify and screen FEPs to develop *scenarios*
- 7 (2) Detailed guidance on the analysis for the protection of the inadvertent intruder
- 8 (3) Detailed guidance and examples for conducting site stability analyses that evaluate the
9 long-term stability of the disposal site and determines compliance with 10 CFR 61.44
- 10 (4) Development of waste acceptance criteria, waste characterization methods, and waste
11 certification
- 12 (5) Risk-informing the analyses for the three-tiered analysis timeframe: the compliance
13 period (1,000 years), the protective assurance period (from 1,000 to 10,000 years), and
14 the performance period analyses (for long-lived waste beyond 10,000 years), using a
15 graded level of effort
- 16 (6) Defense-in-depth analyses that demonstrate the proposed disposal facility includes
17 defense-in-depth protections
- 18 (7) Discussion of a safety case as a collection of information that demonstrates the
19 assessment of the safety of a waste disposal facility
- 20 (8) Performance confirmation and the conduct of periodic reviews for technical analyses and
21 waste acceptance criteria

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

30 **1.3 Document Organization**
31

32 This document provides guidance on conducting technical analyses to demonstrate compliance
33 with the performance objectives of 10 CFR Part 61. This guidance document discusses the
34 parameters and assumptions that can be used in conducting these technical analyses in a
35 broad sense, rather than in a prescriptive manner, to allow flexibility to licensees (see Example
36 1.1). The NRC staff considers this flexibility necessary because the site-specific nature of LLW
37 disposal can make specification of particular models or parameter values impractical.
38 Table 1-1 presents the technical analyses, the relevant requirements in 10 CFR Part 61, and the
39 individual sections of this document where licensees and regulators can find guidance related to
40 the analyses.
41

1 **Table 1-1 Crosswalk between Technical Requirements and Document Sections**

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

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

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

2
3 Section 2.0 summarizes general considerations for conducting technical analyses, such as
4 *model abstraction, model uncertainty, and model support*. Sections 2.0 and 3.0 provide

1 guidance for specific topics related to performance assessment modeling concerned with
2 radiological protection of the general public, as required in 10 CFR 61.41. Section 4.0 provides
3 guidance specific to the analysis required for radiological protection of the inadvertent intruder,
4 as required in 10 CFR 61.42. Section 5.0 provides guidance on stability of the disposal site
5 after closure, as required in 10 CFR 61.44. Section 6.0 discusses the protective assurance
6 period analysis and Section 7.0 provides guidance on the performance period analyses for
7 10 CFR 61.13(e) associated with the disposal of long-lived waste. Section 8.0 discusses the
8 defense-in-depth analysis required under 10 CFR 61.13(f). Section 9.0 discusses the process
9 for waste acceptance, such as developing waste acceptance criteria and performing waste
10 characterization and waste certification. Section 10.0 discusses conducting performance
11 confirmation to evaluate and verify the accuracy of information used to demonstrate compliance
12 prior to site closure. Section 11.0 provides references for the use of other NRC guidance
13 documents. Section 12.0 provides the references cited in this document and Section 13.0
14 contains a glossary of technical terms used in this guidance.

15 **1.4 Risk-Informed Approach**

16
17 This document should be implemented in a risk-informed manner. In NUREG-1614 (NRC,
18 2012b), risk-informed is defined as “an approach to decision-making in which risk insights are
19 considered along with other factors such as engineering judgment, safety limits, and redundant
20 and/or diverse safety systems. Such an approach is used to establish requirements that better
21 focus licensee and regulatory attention on design and operational issues commensurate with
22 their importance to public health and safety.” (e.g., the risk to human health associated with
23 exposure to ionizing radiation). A reviewer should place relatively more emphasis on technical
24 information associated with systems that prevent a risk¹ from being realized or that significantly
25 reduce the magnitude of a risk. Licensees should perform sufficient evaluation and develop
26 adequate bases to identify and emphasize the key areas of the performance assessment,
27 intruder assessment, and site stability evaluation that are expected to have the biggest impact
28 on public health and safety. The type, quantity, and concentration of waste that a facility
29 receives will drive the risk which in turn will drive the level of detail of the assessments.
30

31 Various sections of this document provide risk-informed guidance. Although conducting
32 analyses for the compliance period and the protective assurance period requires projecting
33 doses for up to 10,000 years, the scope, technical bases, and level of detail should be tailored
34 to the waste characteristics. For example, the level of effort required for model support for the
35 performance assessment to demonstrate compliance with 10 CFR 61.41 will most likely be
36 higher than the level of effort that should be expended for the performance period analyses.
37 More robust model support may be needed for the performance period analyses if large
38 quantities and/or high concentrations of long-lived waste are present at the disposal site.
39

40 The approach to the intruder dose assessment described in Section 4.0 provides methods for
41 risk-informing scenario selection by considering site environmental conditions and land use
42 information. The analysis recommended for the site stability evaluation in Section 5.0 will
43 ensure that the complexity of the evaluation is commensurate with the *hazard* of the material
44 that will be disposed.
45

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

2.0 GENERAL TECHNICAL ANALYSES CONSIDERATIONS

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

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

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

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

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

2.1 Assessment Process

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

2.1.1 Terms and Definitions

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

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

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

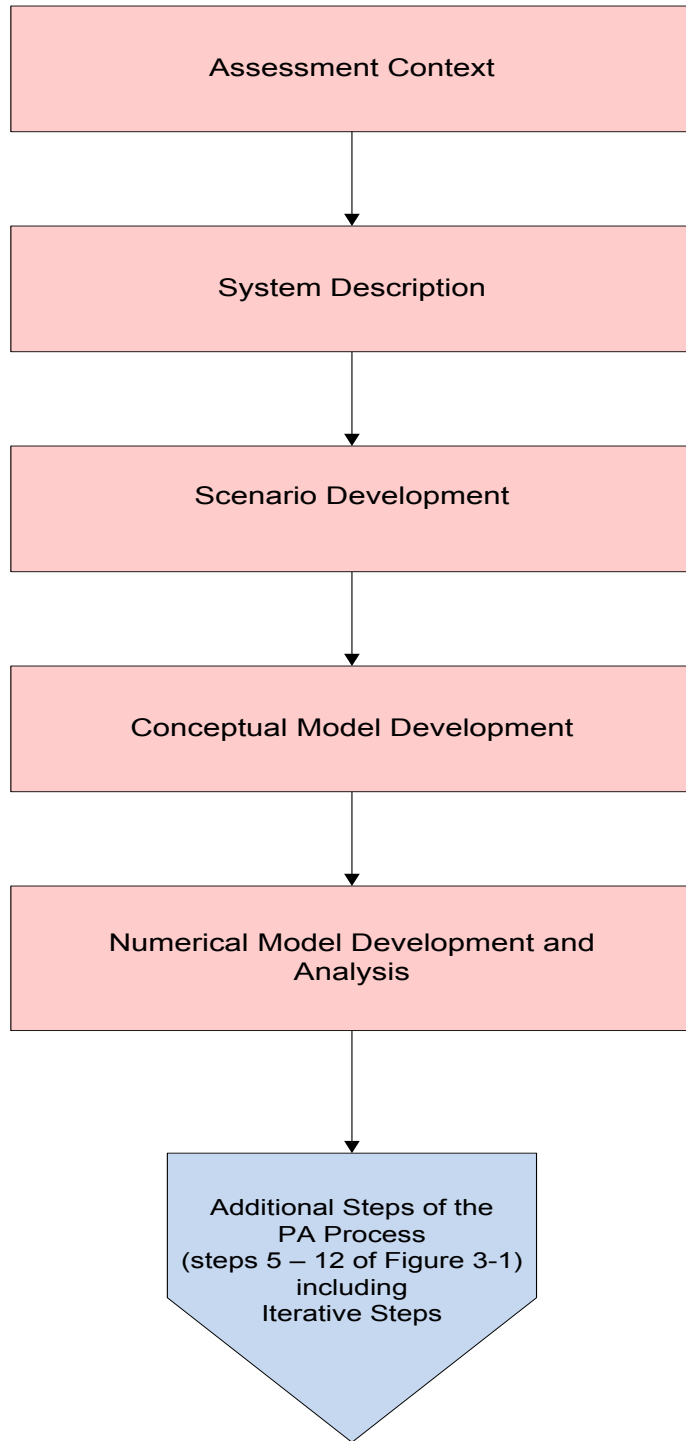
Process is a qualitative or quantitative phenomenon or change that has the potential to affect the performance of the disposal system and that occurs during all or a significant part of the analyses timeframe. Examples of processes that cause relative gradual change are radionuclide transport, differential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

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

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

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

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



1
2
3
4
5

Figure 2-1 Initial Steps of the Performance Assessment Methodology

1
2 *Alternative scenario* is a less likely but still plausible future evolution of the disposal site.
3 Alternative scenarios may include disruptive events if those FEPs are relevant at a particular
4 site.

5
6 *Conceptual model* is a well-defined, connected sequence of phenomena describing the
7 behavior of the system of concern.

8
9 *Alternative conceptual model* is an additional and different model on how the system might work
10 that is consistent with available supporting information. For example, a scenario may have a
11 matrix flow conceptual model and an alternative fracture flow conceptual model; the model
12 outputs from each may yield significantly different results.

13
14 *Receptor scenario* is a type of scenario that describes the FEPs associated with people
15 becoming exposed to radiation.

16
17 *Safety function* is defined qualitatively as a function through which a component of the disposal
18 system contributes to safety and achieves its safety objective throughout the analyses
19 timeframe.

20
21 *Model abstraction* is the process of abstracting a conceptual model representing a dynamic site
22 in the physical world into a *mathematical model* governed by equations that is implemented
23 within a numerical model.

24
25 *Model simplification* is the process of simplifying a complex numerical model into a reduced
26 numerical model while still maintaining the validity of the simulation results.

27
28 *Code* is a set of software commands used to solve mathematical equations representing
29 phenomena of the conceptual model.

30 **2.1.2 Level of Effort**

31
32 LLW commonly contains radionuclides that are both short- and long-lived. From a specific
33 activity standpoint, the short-lived isotopes comprise the dominant fraction of the total activity.
34 However, when a licensee demonstrates compliance with the 10 CFR 61.41(a) performance
35 objective, usually the radiological risk is dominated by the long-lived isotopes that remain in the
36 inventory after the short-lived activity has decayed. LLW may contain large quantities of
37 depleted uranium (DU) or other long-lived waste. LLW may not decrease in *risk* after a few
38 hundred years, although it will decrease in *hazard*. LLW that contains large quantities of DU
39 may pose a long-term risk to the public due to the in-growth of progeny.

40
41 A licensee should use a level of effort for technical analyses commensurate with the risk to the
42 public from disposal of the waste. Specifically, the level of effort (i.e., the level of detail,
43 comprehensiveness, completeness, and degree of iteration), is commensurate to the longevity,
44 concentrations of radionuclides, and quantity of the waste. For example, the level of effort for
45 the development of the technical analyses for the disposal of LLW will generally be less than
46 that for the disposal of HLW or spent nuclear fuel. Complex modeling is generally not
47 performed for disposal sites that contain only short-lived radionuclides and have low projected
48 overall risk.

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

17 **2.2 General Review Considerations**

18 **2.2.1 Data Adequacy**

19
20 It is important for a licensee to develop and use adequate data. The data should be
21 appropriately representative and complete, of adequate quality, and unbiased. The objective of
22 the data adequacy review is twofold. First, the reviewer should determine whether sufficient
23 data have been provided by a licensee to support the performance assessment models.
24 Second, the reviewer should determine whether those data have been used appropriately.

25
26 It is generally beneficial to have more data rather than less; however, some amount of
27 incompleteness in the data may be overcome by appropriately accounting for parameter
28 uncertainty, as described in Section 2.2.2.1.2. The types of data to be considered by licensees
29 may include, but are not limited to site-specific data (e.g., laboratory measurements and field-
30 scale measurements or experiments), data from analogous sites, data from generic sources,
31 output from detailed process-level models, and expert judgment. More objective sources of
32 data are preferred over more subjective sources of data. A licensee should review published
33 literature even if they have made site-specific measurements. Review of published literature
34 may help the licensee identify measurement errors or determine if the data is not representative.
35 Expert judgment should be used by licensees as a last resort, assigned appropriate uncertainty,
36 and completed with a formal expert elicitation process when the data are important to the
37 performance assessment (NRC, 1996). Because performance assessments are completed with
38 an iterative process, early data for scoping calculations may be from more subjective sources
39 (e.g., informal expert judgment). If a licensee or regulator determines during independent
40 analysis that certain data are risks significant; the data should be developed by more objective
41 sources, when possible.

42
43 Because performance assessment models can simulate processes and events over a wide
44 range of temporal and spatial scales, licensees should ensure that the data are representative
45 of the temporal and spatial scales evaluated in the model. *Upscaling* of data may be necessary
46 to achieve representativeness. Upscaling is the modification of data for use at a different scale,
47 most commonly to take data from fine-scale observations for use at a much coarser scale. If a

1 licensee uses upscaling to modify data for use at different scales, they should ensure that the
2 key features or structure of the data important to the performance assessment are preserved.
3 For example, precipitation may occur as short duration storm events (minutes to hours),
4 whereas the timeframe for a performance assessment is thousands of years. If a performance
5 impact, such as erosion of a soil cover, is a non-linear function of runoff that itself is a function of
6 precipitation intensity and duration, upscaling of the temporal precipitation data in order to
7 develop the performance assessment calculations may result in the loss of important detail.
8 Licensees should use caution when estimating whether measurements are outliers, particularly
9 when the number of measurements is sparse. Licensees should not use subjective
10 assessments of potential outliers.

11 **2.2.2 Uncertainty**

12
13 Sources of uncertainty inherent to waste disposal in the near surface include, but are not limited
14 to, incomplete knowledge of the natural system, its evolution, and interactions. Regulators
15 expect that uncertainties that cannot be shown by a licensee to have a minimal effect on safety
16 are avoided or reduced as far as possible (e.g., by means of site selection, site characterization,
17 disposal design, and, if necessary, research). To some extent, uncertainties in the assessment
18 results can be counterbalanced by using multiple lines of evidence, or model support.
19 Licensees should characterize, eliminate (with justification), or bound uncertainties in their
20 technical analyses, as well as document the impact of the uncertainties on performance.

21
22 The uncertainties in performance assessment have been classified as *scenario uncertainty*,
23 model uncertainty (which spans conceptual model uncertainty and mathematical model
24 uncertainty), and parameter uncertainty (i.e., uncertainty in values used in the numerical model)
25 (NRC, 1990a). Scenario uncertainty, defined as the consideration of uncertainty in the future
26 evolution of the site, may result in several different conceptual models for the system,
27 distinguished by the effects of phenomena on the system. Model uncertainty may be present in
28 each of the different submodels that comprise the overall system model. Licensees can
29 evaluate these inherent uncertainties using *uncertainty analysis*, which is a way of formally
30 assessing, reducing or managing, and documenting the inherent uncertainty of a system
31 (Finkel, 1990). For example, an uncertainty analysis could provide information about where a
32 licensee should focus model support activities, which in turn could reduce uncertainty.
33 Parameter uncertainty is uncertainty in the parameters used in the technical analyses.

34 **2.2.2.1 General Structure of Uncertainty**

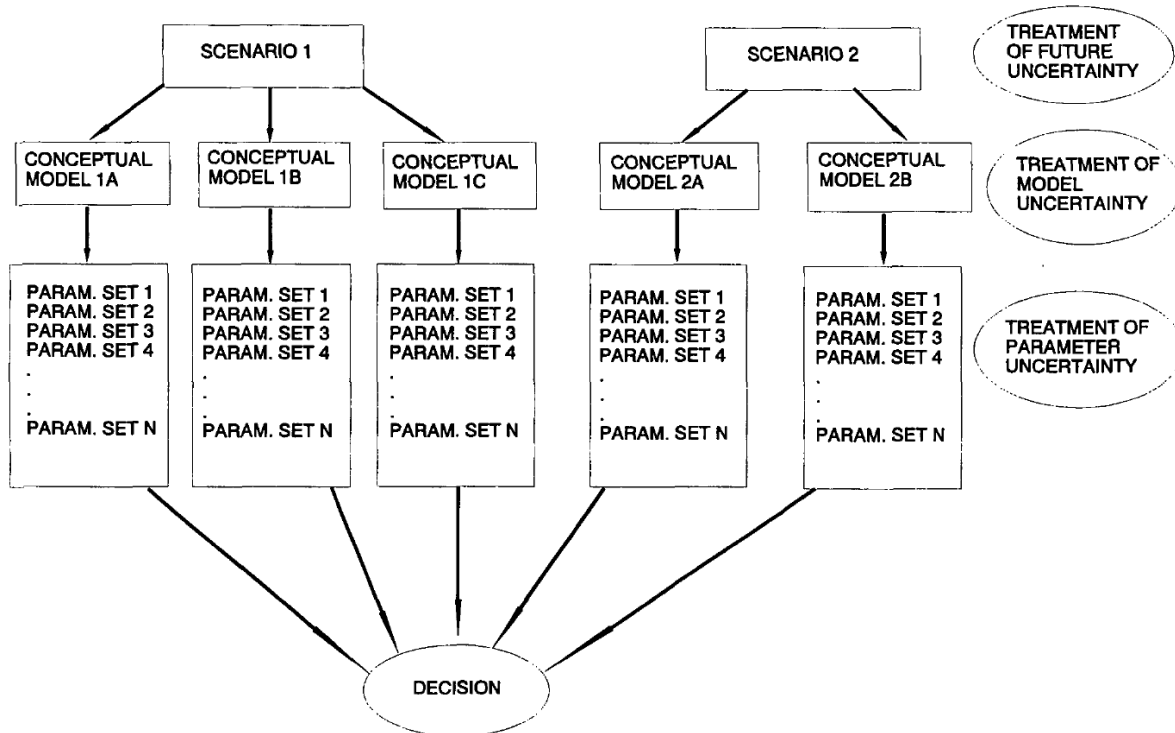
35
36 Some radioactive waste will present a radiological risk to humans and the environment for a
37 long time. To help assess this risk, licensees should use predictive models that can describe
38 the future behavior or performance of disposal systems. Building a *computational model* that
39 combines and represents all important FEPs at an appropriate level of detail is a complex
40 process. Uncertainties are greater for long-lived waste (lasting thousands of years or longer)
41 than they are for short-lived wastes (lasting tens or hundreds of years). Uncertainties must be
42 handled by licensees within the performance assessment process. Scenario development is a
43 commonly used technique to account for uncertainties about the future.

44
45 Figure 2-2 shows a general structure of uncertainty analysis that involves separate treatments
46 of scenario uncertainty (future uncertainty), model uncertainty, and parameter uncertainty (NRC,
47 1993a). Within each scenario of the future, it is possible to postulate alternative conceptual

1 models of the behavior of the disposal system, each of which leads to a particular mathematical
 2 model to describe that behavior. For each conceptual model, it is possible to postulate
 3 alternative sets of input parameter values. In the context of performance assessment for LLW
 4 disposal, the primary purpose of an uncertainty analysis is to support a decision about
 5 compliance of the disposal system with the regulatory requirements.

6 2.2.2.1.1 Scenario Uncertainty

7
 8 Uncertainty about the future of the site is the result of inherent lack of knowledge about how the
 9 site will evolve over time. The future climatic, geologic, and population conditions that will
 10 prevail at a site are not known, but the performance assessment process requires that a
 11 licensee consider possible future conditions. Scenario uncertainties are illustrated by
 12 considering the events or processes that may significantly influence projected doses to the
 13 receptor. For example, climatic variation may significantly change groundwater flow pathways
 14 over time, necessitating changes to the groundwater flow model or the introduction of new
 15 parameters. If analyses cannot exclude the possibility of either scenario 1) where the
 16 groundwater flow pathways remain unchanged (no major climate variation), or 2) where the
 17 groundwater flow pathways change (climate variation), then the site has two potential routes of
 18 evolutionary development (i.e., two future scenarios that need to be analyzed in this example).
 19 The longer the *analysis timeframe*, the greater the likelihood of significant changes to the flow
 20 path and properties. Scenario uncertainty is linked to, but not identical with, future parameter
 21 uncertainty, which is discussed in the next section.
 22



23
 24 **Figure 2-2 Overall Approach to Uncertainty Analysis for LLW Performance**
 25 **Assessment (NRC, 1993a)**

1 2.2.2.1.2 *Model Uncertainty*

2
3 Model uncertainty encompasses the uncertainty in the conceptualization of the system, the
4 uncertainty in its mathematical representation, and the uncertainty in the solution of the
5 mathematical representation (Bonano and Cranwell, 1988). All models will encompass some
6 simplification of reality (model abstraction) and licensees will have to make a variety of choices
7 about the level of detail to provide.

8
9 Conceptual model uncertainty is generally the dominant type of uncertainty in a performance
10 assessment due to limitations in the available supporting data. The conceptual model should be
11 as complete and as appropriate to the scenario as possible. The conceptual model should be
12 based on the information and data available and on previous experience with similar types of
13 problems. If not all significant processes, features, or significant barriers have been considered,
14 the conceptual model will have deficiencies and the ability of the licensee to bound or otherwise
15 account for model uncertainty will be reduced (BIOMOVs II, 1996).

16
17 Licensees should adequately describe and document conceptual model uncertainties. The
18 performance assessment documentation should provide the assumptions, limitations, and
19 uncertainties of the models. Multiple representations of a model or different models may be
20 consistent with the available data. In general, licensees should select the models that best
21 represent available data. However, when data are sparse, multiple models may represent the
22 available data. In this case, licensees should select the model that provides the most
23 conservative result, or collect additional data to determine which alternative conceptual model
24 provides the best representation. Licensees do not need to evaluate all models, but they should
25 consider all models that are reasonably consistent with available information. Regulators
26 should perform an independent evaluation of model uncertainty and consider whether more
27 than one conceptual model should be evaluated, especially for complex sites.

28
29 Other types of model uncertainty include assumptions, decisions or judgments made during the
30 development of a model, the mathematical form of the conceptual models, and the inexact
31 implementation of mathematical models in numerical form in computer codes. Related
32 computer model uncertainties can arise from errors in the computer code used to develop the
33 model, input data errors, misapplication of the code (e.g., through application of the code to
34 problems beyond the range for which the code was developed), and approximations in the
35 solution of the mathematical model (e.g., due to inappropriate grid discretization of a domain or
36 setting time steps that are too large).

37
38 The objective of the review of model uncertainty is for the reviewer to determine if the licensee
39 has considered and appropriately evaluated the impact of model uncertainty. Some
40 uncertainties are inherent in the application of predictive models to (1) long periods of time for
41 which direct *validation* is not possible, and (2) complex systems for which measurement and
42 characterization may be limited. These uncertainties can be evaluated in the performance
43 assessment by (1) considering reasonable ranges in conditions and processes to test the
44 robustness of the model, (2) by using distributions of parameters to represent the likely ranges
45 in conditions or processes, or (3) by bounding the effects of model uncertainty by using
46 conservative assumptions. Ideally, a licensee can minimize the impact of model uncertainty by
47 developing as much model support as practical (see Section 2.2.3).

1 2.2.2.1.3 *Parameter Uncertainty*

2
3 Parameter uncertainty can be reducible or irreducible. Technical analyses will need to account
4 for parameter uncertainty. Although evaluation of parameter uncertainty does not specifically
5 address scenario uncertainty, parameter values are the building blocks of any model and
6 therefore, spatial or temporal variations in parameter values are often needed to reflect the
7 evolution of a site, as well as to evaluate the impact of different representations of what might
8 happen in the future. For example, the range of flow rates through a hydrogeological unit may
9 increase over time within one plausible scenario. In an alternative, drier scenario, the same
10 hydrogeological unit will start out with the same flow rate, but, in contrast with the previous
11 scenario, may decrease over time.

12
13 The objective of the review of parameter uncertainty is to determine if the assessment by the
14 licensee includes parameter uncertainty, which techniques were used to account for parameter
15 uncertainty, and whether those techniques adequately accounted for parameter uncertainty.
16 Selection of conservative values is one method a licensee may use to account for parameter
17 uncertainty. This method works well when the number of uncertain parameters is limited and
18 conservative values can be clearly established. This method may not work well when there are
19 many uncertain parameters, especially for complex models. This should not be interpreted by
20 licensees or regulators to mean that conservative values should not be used for complex sites,
21 but rather that licensees should demonstrate sufficient knowledge of their performance
22 assessment so that conservative selections can be reliably made. Variations in the model
23 responses, such as local minima and maxima data values, can make the determination of
24 conservative parameter values very challenging.

25
26 Another method to incorporate parameter uncertainty is the use of some form of *probabilistic*
27 *analysis*. Parameter uncertainty can be propagated through the performance assessment by
28 distributions of variables (e.g., hydraulic conductivity, porosity, *distribution coefficient*). When
29 using probabilistic analysis, licensees should plot measured data on figures showing the
30 probability distributions assigned to represent the measured data in the modeling to
31 communicate (1) the amount of data available to construct the distribution, and (2) how the
32 selected distribution reflects the data. Licensees should preserve the correlation of data for
33 related parameters (e.g., precipitation and irrigation rate) in probabilistic analysis, as necessary.
34 Performance assessments that rely on a large amount of generic data (e.g., non-site-specific)
35 will have comparatively more uncertainty, as discussed in Section 2.2.3. In a *deterministic*
36 *analysis*, licensees can examine the impact of parameter uncertainty with sensitivity analyses.
37 They can then bound impacts by the selection of conservative values. Section 2.7.4 provides a
38 discussion of some significant challenges with this approach, as well as the metrics to use for
39 determining compliance (i.e., the peak of the mean).

40 2.2.2.1.4 *Uncertainty Example—Transfer Factors*

41
42 One acceptable quantitative approach for modeling the transport of radionuclides through the
43 biosphere employs steady-state transfer factors (e.g., soil to plant, water to biota) and
44 bioaccumulation factors. The literature contains many sources for these transfer factors
45 (Staven et al., 2003; IAEA, 1994; NRC, 1992; Wang et al., 1993; Baes et al., 1984; NRC, 2007c;
46 NRC, 2003a). Regulatory Guide 1.109, Revision 1, “Calculation of Annual Doses to Man from
47 Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with
48 10 CFR Part 50, Appendix I,” issued October 1977, provides conservative values for a variety of

1 these factors (NRC, 1977). If available, licensees should use site-specific parameter values or
2 ranges of values, and should document their usage. Site-specific parameter values are values
3 measured at the site under consideration; true site-specific values are relatively rare. If site-
4 specific transfer factors are not available, a licensee should document how their site conditions
5 are comparable to the conditions under which the transfer factors that were used were
6 collected. Licensees can infer transfer factors for a specific site from compilations in the
7 literature; however, inferred values carry high uncertainty, which can be difficult to properly
8 account for in a deterministic assessment.

9
10 Transfer factors can have very large variances and be non-uniformly distributed. These large
11 variances may require careful treatment in the intruder assessment or performance
12 assessment. If a transfer factor has few observations and the actual observations span many
13 orders of magnitude, the appropriate statistic of the inferred distribution to use in the technical
14 analysis may be difficult to determine. This is because the observations represent both inter-
15 site and intra-site variability. The technical analysis should not benefit from inter-site variability.
16 Use of the geometric mean, for example, may result in a high likelihood that data that are not
17 representative of the specific site have been “credited” in the analysis. Even if intra-site values
18 are used to extend the “conservative” end of the distribution (e.g., high values of transfer
19 coefficients), the overall effect may not be conservative because overly broad uncertainty
20 ranges can lead to risk dilution (Section 2.7.4). If no observations at a site are available and
21 correlations between the specific site conditions and the conditions for which the observations
22 were made are not available, then licensees should use conservative statistics for transfer
23 factors in deterministic analyses. In probabilistic analyses, licensees can use the full non-
24 truncated distribution (assuming the results are still physically reasonable), and use uncertainty
25 analyses to determine if the uncertainty in the transfer factors is important. If the uncertainty is
26 important, then licensees must provide a technical basis to explain why the distribution that
27 contains inter-site variability used for the technical analysis is protective of public health and
28 safety, or the licensee may elect to collect additional site characterization data to better define
29 the range and variability.

30 **2.2.3 Model Support**

31
32 Model support is one of the most essential technical elements of a licensee’s analyses to
33 demonstrate compliance with the Subpart C performance objectives. Performance
34 assessments and site stability assessments are projections many years into the future, and
35 therefore, cannot be validated in the traditional sense. Intruder assessments are based on
36 plausible but hypothetical scenarios. However, support for the calculations is essential for
37 effective decisionmaking. Model support can help reduce uncertainty and provide a mechanism
38 to determine when sufficient iteration in the development process has been performed.
39 Regulatory perspectives on model validation for HLW disposal are provided in NUREG-1636
40 (NRC, 1999a). Many of the concepts found in NUREG-1636 are generic and are applicable to
41 LLW disposal as well.

42
43 Model support can be divided into verification-type activities (i.e., determining that the equations
44 were solved correctly) and validation-type activities (i.e., determining that the correct equations
45 were solved). Methods for *verification* of computational models are reasonably well-established.

46
47 The objective of the review of model support is to determine if the technical analyses have
48 adequate support to justify the estimated system performance. In addition to reviewing a

1 licensee's QA procedures for computational modeling, the reviewer may perform independent
2 analyses. Independent analyses may be performed with the licensee's models, with
3 independent models, or with simplified calculations. The objectives of independent analyses
4 are to test, confirm, or refute the licensee's assumptions and analyses.
5

6 Because the primary output of a performance assessment is dose to the public and those doses
7 are in most cases not expected to occur until the distant future, the performance assessment
8 cannot be supported by comparing the modeled dose to observed doses. However, a
9 performance assessment typically includes many submodels that estimate the impact of
10 processes such as infiltration, leaching of radionuclides from waste, and transport through
11 groundwater. Licensees can and should support the output from those submodels using
12 indirect methods if the output from the submodels is not observable in the real world. Model
13 support that involves multiple sources and types of information is generally more robust. Types
14 of model support may include laboratory or field tests, comparison to analogous systems,
15 natural analogs, independent process modeling, formal independent peer review, and
16 comparison to *monitoring* data.
17

18 Upon development, and through early iterations, the performance assessment model (or
19 submodels) is likely to go through a formal or informal calibration process. Calibration is a
20 comparison of calculated outputs (e.g., intermediate outputs such as hydraulic head in an
21 aquifer) with measured or observed data resulting in changes to the numerical calculation to
22 better represent the observed data. While calibration is important, it does not necessarily result
23 in confidence in prediction. Confidence in prediction is derived through comparison of the
24 model with independent data not used in the original development or calibration of the model.
25 Absolute proof cannot be achieved in performance assessment modeling; however, adequate
26 confidence in the model and modeling results is essential.
27

28 The quantity and quality of model support should be commensurate with the significance of the
29 system/subsystem to achieving protection. For example, if the capabilities needed for an
30 engineered barrier are consistent with past experience in similar conditions, and the barriers
31 have similar design and quality assurance (QA), then the model support could be considerably
32 less than for a barrier with projected capabilities that significantly exceed experience with similar
33 barriers. When considering prior experience, licensees should ensure that the environmental
34 conditions for the relevant degradation mechanisms are reasonably similar since many
35 degradation mechanisms can be very sensitive to the environmental exposure conditions.
36

37 Performance assessment modeling may include the projection of performance of engineered
38 barriers, such as engineered covers or intruder barriers, for long periods of time. Licensees
39 should consider natural analogs for barriers desired to have very long-term capabilities (e.g.,
40 thousands of years). The greatest uncertainties in predicting future performance stem from
41 extrapolating the results of short-term tests and observations to long-term performance.
42 Standard approaches to development of natural analogs frequently assume implicitly that the
43 initial conditions persist; however, the actual application of a barrier could more appropriately be
44 viewed as an evolving component of a larger dynamic system (Waugh and Richardson, 1997).
45 For some types of barriers, natural analogs might provide information about the possible long-
46 term changes and can be thought of as a long-term, uncontrolled experiment.
47

48 Licensees should consider the capability of a barrier when developing model support based on
49 analogs. For example, because of their longevity, Native American earthen mounds may

1 provide a reasonable analog for the erosional stability of an engineered cap, but may not be a
2 reasonable analog for other capabilities (e.g., the hydraulic performance of a cap) (Shetrone,
3 2004). When evaluating analogs, it is important to note that the structures that have persisted
4 are most likely the durable structures. That is why licensees should consider analogs that have
5 persisted, as well as those that may have experienced damage or failure. An additional
6 complicating factor is that the initial conditions and past exposure environment for the analogs
7 are not known and may only be estimated. However, developing an understanding of analogs
8 increases the likelihood that a barrier may be implemented with sustainable long-term
9 capabilities. Natural analogs are only one element of the technical basis for the capabilities of
10 engineered barriers. Analog information should not be envisioned as providing absolute proof
11 of future barrier performance; rather, it provides confidence that the barrier is likely to perform
12 as intended. Analog information can be also applied to other aspects of the performance assessment
13 models (e.g., radionuclide transport, geochemistry).

14 **2.2.3.1 Peer Review, Expert Judgment, and Expert Elicitation**

15
16 Different types of assessments are used in the development, review, and approval of LLW
17 technical analyses. Scientists and engineers routinely use professional judgment in solving
18 problems. NUREG-1563, "Branch Technical Position on the Use of Expert Elicitation in the
19 High-Level Radioactive Waste Program," issued November 1996, defines "peer review," "expert
20 judgment," and "expert elicitation" as applied to HLW disposal (NRC, 1996). The NRC staff
21 believes that those definitions and descriptions also can be applied to LLW disposal. The
22 purpose of this section is to provide a concise summary of information pertaining to the use of
23 experts and to remind licensees of existing sources of guidance. Methods of reviewing or
24 supplying information to technical analyses may have different degrees of formality and
25 independence. Information from experts is necessary when other means of obtaining requisite
26 data or information are not practical. The types of information that experts can supply include
27 data (e.g., hydraulic conductivity of basalt), as well as input analogous to model support
28 (e.g., independent peer review of a hydrogeology model).

29
30 Peer review is distinguished from expert judgment in that peer review seeks judgments from
31 experts regarding the soundness and quality of an existing or proposed scientific stance or
32 solution to a problem. Expert judgment is information provided by experts that gives rise to or
33 contributes to the generation of a scientific stance or solution to a given problem. Expert
34 elicitation is a formal, highly structured, and well-documented process whereby expert
35 judgments are obtained (NRC, 1996). The regulatory review of LLW technical analyses is
36 essentially an independent peer review.

37
38 For all types of information obtained from experts, licensees should describe and fully document
39 the information developed as well as the process used to obtain the information. Full
40 documentation entails a description in sufficient detail to allow independent interpretation and
41 understanding of the information without recourse to the author. Licensees should establish
42 and describe the independence of the experts and their qualifications.

43
44 If a licensee uses peer review as a form of model support, the experts should have
45 independence from the activity for their input to be of value. Otherwise, the input is essentially
46 an extension of the original analysis. The licensee should document how the experts were
47 selected and their qualifications. Licensees should describe the information that the experts
48 reviewed and document when the experts' review and input was received. In other words,

1 scope and schedule are important in establishing the thoroughness of the review. The experts'
2 reviews should have sufficient detail for independent evaluation by the regulator. Independent
3 peer review is more subjective than some other forms of model support (e.g., field experiments)
4 but may be necessary to support the technical analyses for LLW disposal.

5
6 Expert elicitation and expert judgment are means to supply information such as uncertain values
7 or uncertainty distributions when data are unavailable or inadequate and cannot be obtained
8 with direct methods such as experiments. Expert elicitation and judgment characterize the state
9 of knowledge about an uncertain FEP. Expert elicitation and judgment should not be used
10 instead of "hard" data, but rather in conjunction with those data. NUREG-1563 provides general
11 guidelines on those circumstances that may warrant the use of a formal process for obtaining
12 judgments of experts, as well as acceptable procedures for conducting expert elicitation (NRC,
13 1996).

14 **2.2.3.2 Model Support Example –Engineered Cover Performance**

15
16 The NRC staff is providing the following example to illustrate a reasonable effort to develop
17 model support for the long-term performance of an engineered system. The DOE, Office of
18 Legacy Management, Environmental Sciences Laboratory, developed a multi-faceted strategy
19 combining monitoring, modeling, and natural analog studies to provide support for the estimated
20 long-term performance of engineered covers (Waugh, 2004; Waugh 2006). The strategy
21 utilized various independent sources of information to develop an understanding of the
22 performance of engineered covers. Laboratory experiments (e.g., the hydraulic conductivity of
23 clay), field measurements (e.g., the moisture content of the cover materials and tailings), in-situ
24 field tests (e.g., lysimeter studies), natural analogs, and traditional monitoring data (e.g., radon
25 fluxes, groundwater concentrations of radionuclides) provided information to compare to
26 estimates of cover performance. There is uncertainty in any type of observational data.
27 However, utilization of multiple sources of confirmatory information allows for the development
28 of a more complete understanding of the uncertainties, and therefore, a lessened chance of
29 false positive or false negative confirmation of system performance.

30
31 As part of the model support strategy, DOE obtained field measurements using lysimeters to
32 test the performance of cover designs under the Alternative Cover Assessment Project (ACAP)
33 (Albright et al., 2004). DOE performed comprehensive lysimeter tests of prototype covers at
34 landfill sites across the country in climates ranging from arid to humid and from hot to cold.
35 Some of the cover sites were at locations of full-scale covers operated by DOE. DOE monitored
36 both conventional, low-permeability and alternative evapotranspiration cover designs in side-by-
37 side comparisons. The ACAP prototype tests were conducted using 10- by 20-meter drainage
38 lysimeters instrumented for direct measurement of runoff, soil water storage, lateral drainage,
39 and percolation flux for a full-depth cover profile. DOE used the lysimeter monitoring data to
40 develop insights into cover performance.

41
42 Because some processes that may influence the performance of engineered covers are difficult
43 to address with short-term field tests or existing numerical models, DOE also used natural
44 analogs to help identify and evaluate likely changes in environmental processes that may
45 influence the performance of engineered covers (Waugh, 2006). DOE used the natural analog
46 information to (1) engineer cover systems that mimic favorable natural systems, (2) bound
47 possible future conditions for input to predictive models and field tests, and (3) provide insights
48 about the possible evolution of engineered covers as a basis for monitoring leading indicators of

1 change. DOE considered a variety of natural analogs, including analogs of future climate states
2 at the Monticello, Utah site that were developed using paleoclimate data. A preliminary analysis
3 of paleoclimate data for Monticello yielded average annual temperature and precipitation ranges
4 of 2 to 10 degrees C and 80 to 60 centimeters, respectively, corresponding to late glacial and
5 mid-Holocene periods. Additional natural analogs were developed for future soil development
6 and ecological change.

7 **2.2.4 Dose Assessment**

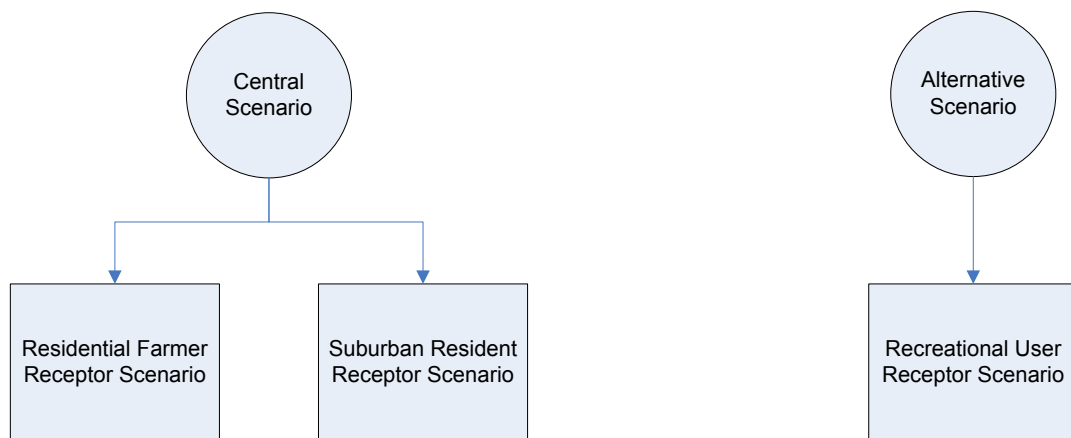
8 **2.2.4.1 Human Activity - Scenarios**

9
10 Stylized scenarios are commonly defined to represent the human component of the analyses.
11 Little scientific basis exists for predicting the nature or probability of future human actions over
12 long timeframes. The use of stylized scenarios is commonly advocated by regulators in order to
13 avoid excessive speculation. A special category of FEPs are those related to future human
14 activities that may disrupt the disposal system. Section 4.0 provides guidance on developing
15 scenarios for the inadvertent intruder assessment. 10 CFR Part 61 requires the consideration
16 of inadvertent intrusion, and also, to some extent, constrains the types of receptor scenarios
17 that need to be considered.

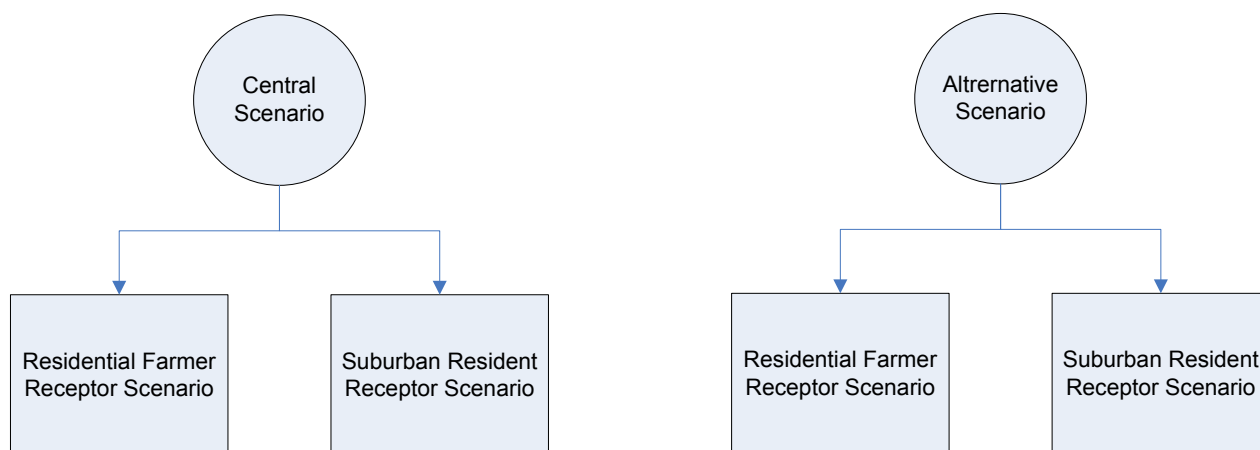
18
19 Licensees should integrate receptor scenarios with the scenarios describing the future evolution
20 of the disposal site. For example, the landscape and hydrological regime at and around a
21 hypothetical disposal site may change in response to climate change, and with these changes,
22 receptors and their habits may change. The central scenario for this hypothetical disposal site
23 may include *exposure pathways* that result in multiple receptor scenarios. For example, the
24 most plausible and/or conservative receptor scenarios for an undisturbed central scenario may
25 be the resident farmer and suburban resident receptor scenarios. However, if a licensee is
26 evaluating an additional alternative scenario of the future involving climate change for the same
27 site, the most plausible receptor scenario for the alternative scenario may no longer favor
28 residential dwellings at the site, but may be, for example, occasional recreational use of the site
29 by one or more human receptors (Figure 2-3). On the other hand, it is possible that the receptor
30 scenarios may remain the same (i.e., the resident farmer and suburban resident receptor
31 scenarios would be evaluated within the undisturbed future scenario and within the alternative
32 scenario involving climate change) but the dominant pathways of exposure may change within
33 the same scenario (i.e., irrigation rates increase resulting in additional exposure through food).
34 (Figure 2-4).

35 **2.2.4.2 Receptor Scenario Development**

36
37 After releases of radioactivity to the environment, a receptor may be exposed to contaminated
38 water, soil, air, or other media. A receptor is a *member of the public* who may be exposed to
39 radiation from the disposal facility. Receptors include members of the public who may be on
40 site after the institutional control period (e.g., an inadvertent intruder), as well as offsite
41 members of the public. Section 3.4 provides guidance with respect to receptors for the
42 performance assessment. Section 4.3 provides guidance with respect to receptors for the
43 intruder assessment. Some of the approaches used in Section 4.3 can be applied in the
44 performance assessment and used to demonstrate compliance with 10 CFR 61.41.
45



1
2
3 **Figure 2-3 A Central Scenario with Several Plausible Receptor Scenarios, and an**
4 **Alternative Scenario with a Different Plausible Receptor Scenario**



5
6
7 **Figure 2-4 A Central Scenario with Several Plausible Receptor Scenarios, and an**
8 **Alternative Scenario with the Same Plausible Receptor Scenarios**

9
10 Licensees should estimate potential exposure to the average member of the *critical group*. The
11 critical group is a group of individuals reasonably expected to receive the greatest exposure to
12 releases over time, given the circumstances under which the analysis would be carried out.
13 The average member of the critical group is that individual who is assumed to represent the
14 most likely exposure situation, based on cautious but reasonable exposure assumptions and
15 parameter values.

16
17 Scenarios of receptor exposure, also known as *exposure scenarios* or receptor scenarios,
18 should not be confused with the general scenarios describing a future evolution of the disposal
19 system. Receptor scenarios are a subset of the overall scenarios defined for the performance
20 assessment (e.g., base or central scenario, disturbed or alternative performance scenarios) and
21 intruder assessment (Figure 2-4). Receptor characteristics and receptor scenarios may vary
22 from site to site; however, certain pathways commonly contribute to exposure to or intake of
23 radionuclides. For example, drinking water and agricultural food production (crops, livestock)

1 commonly contribute to radionuclide intake by many types of receptors. External exposure to
2 contaminated soils and inhalation of resuspended contaminants are also common exposure
3 pathways. Recreational use of surface water (e.g., fishing and swimming, which may lead to
4 exposure to contaminated sediments) may be an exposure pathway at some sites.
5

6 The characteristics of receptor scenarios can have a large impact on the projected risks from
7 the disposal facility. The definition of receptor scenarios can be generic or site-specific.
8 Regardless of the specific method used to develop receptor scenarios, the licensee should
9 provide sufficient justification for the approach used. Licensees may use generic receptor
10 scenarios as described in NUREG-0782 (NRC, 1981a) with site-specific waste streams, or they
11 may develop site-specific receptor scenarios to evaluate site-specific waste streams. Licensees
12 may develop site-specific receptor scenarios by modifying the exposure pathways included in
13 the generic receptor scenarios or build scenarios from scratch based on waste characteristics,
14 disposal practices, site characteristics, and, when appropriate, projected land use. As the
15 assessment time increases from the present day, the relevance of current land use to projected
16 future land use becomes much more uncertain. For long-term assessments, dose calculations
17 should use reasonably conservative receptor scenarios such as the generic receptor scenarios
18 (i.e., resident-farmer or resident-gardener). The NRC staff continues to view the generic
19 receptor scenarios as reasonably conservative to estimate potential radiological exposures to a
20 member of the public while limiting excessive speculation about future human activities.
21 Licensees should be cautious about adopting the generic receptor scenarios *and* exposure
22 pathways by ensuring that the exposure pathways are appropriate for the technical analysis for
23 their disposal site.
24

25 Licensees should provide a basis to justify receptor scenario selections. Use of conservative
26 generic receptor scenarios would require a limited basis, whereas use of novel site-specific
27 receptor scenarios would require more information. There may be a need to thoroughly
28 investigate and justify the appropriateness of the selected site-specific receptor scenario(s),
29 which may include evaluation of alternate receptor scenarios. If a licensee creates a receptor
30 scenario based on site-specific conditions, it should provide transparent and traceable
31 documentation of the justification for each assumption used in developing the receptor scenario
32 (e.g., justify the inclusion (or exclusion) of a particular exposure pathway).
33

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

1 Determination of the receptor location should also consider the evolution of the site environment
2 during the compliance period. For instance, climate change over the compliance period may
3 alter whether the groundwater is potable or of sufficient yield and thus, potentially, the location
4 of the offsite receptor well.
5

6 A site-specific assessment would typically consider climatic and environmental conditions. As
7 discussed in NUREG-1573, performance assessments should consider variability in natural
8 conditions, processes, and events (NRC, 2000a). The selection of receptor scenarios and
9 pathways in the performance assessment and intruder assessment should consider the
10 variability in natural conditions. For a typical commercial LLW disposal facility, where the
11 hazard from the inventory remaining at 500-1,000 years is expected to be low and allowable
12 limits on long-lived radionuclides can be set, licensees should avoid unnecessary speculation
13 about major changes to future climate (such as glacier formation). This is because the human
14 population would be dramatically affected by the natural process, and the radiological impacts
15 would likely be secondary (in part because the inventory of long-lived waste is limited).
16 However, licensees should consider more gradual changes in performance assessment
17 modeling for significant quantities of long-lived radionuclides, especially for performance period
18 analyses (Section 7.0). For example, natural cycling of climates may induce variation in the
19 nature, timing, and magnitude of meteorological processes and events. For long-lived waste
20 streams, licensees should consider these gradual changes when evaluating impacts to
21 members of the public. If a licensee uses current site conditions to eliminate what would
22 otherwise be considered credible land use (receptor) scenarios and the waste is long-lived, the
23 performance assessment and intruder dose assessment should consider expected changes to
24 climate and environmental conditions as a result of natural cycling of the climate. Changes to
25 the climate may make the eliminated land use (receptor) scenarios more or less likely to occur
26 in the future.
27

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

39 **2.2.4.3 Dosimetry**

40
41 As described in 10 CFR 61.7(c)(5), the dose methodology used to demonstrate compliance with
42 the performance objectives of 10 CFR Part 61 shall be consistent with the dose methodology
43 specified in the standards for radiation protection set forth in 10 CFR Part 20, "Standards for
44 Protection against Radiation." The dose methodology is how individual dose factors (for
45 example: external, ingestion, or inhalation) are calculated for each radionuclide. Licensees may
46 use updated dose factors, which have been issued by consensus scientific organizations and
47 incorporated by the U.S. Environmental Protection Agency (EPA) into Federal radiation
48 guidance. Additionally, licensees may use the most current scientific models and

1 methodologies (e.g., those accepted by the International Commission on Radiological
2 Protection [ICRP]) appropriate for site-specific circumstances to calculate the dose.

3
4 In the performance assessment and intruder assessment, licensees may use the dose
5 conversion factors for inhalation and ingestion developed by the EPA as published in EPA-
6 520/1-88-020, Federal Guidance Report (FGR) No. 11, "Limiting Values of Radionuclide Intake
7 and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion,"
8 issued September 1988 (EPA, 1988). Similarly, it is appropriate for a licensee to use EPA's
9 external dose factors as published in EPA-402-R-93-081, Federal Guidance Report No. 12,
10 "External Exposure to Radionuclides in Air, Water, and Soil," issued September 1993 (EPA,
11 1993). These dose factors are selected to ensure consistency of the *dosimetry* models used in
12 deriving these factors with 10 CFR Part 20, "Standards for Protection against Radiation."
13

14 Dose conversion factors are further defined by the chemical form of each element, by either its
15 gastrointestinal tract uptake fraction (known as the f_1 factor for ingestion dose factors), or its
16 solubility class (solubility in lung fluid for inhalation dose factors). Licensees should provide
17 justification in the performance assessment and intruder assessment for the chemical forms
18 assumed, particularly if a radionuclide has more than one value (e.g., strontium or uranium).
19 Licensees should use reasonably conservative solubility classes for modeling radionuclides in a
20 performance assessment, considering that the element may change in chemical form as it
21 moves through the environment before reaching receptors. For acute *intruder scenarios*,
22 different sets of chemical forms may be expected as the chemical forms of radionuclides in the
23 disposal unit environment may differ from those in the external natural environment.
24

25 An example of a conservative approach to selecting dose factors is used in NUREG/CR-5512,
26 "Residual Radioactive Contamination from Decommissioning, Technical Basis for Translating
27 Contamination Levels for Annual *Total Effective Dose Equivalent*," issued October 1992 (NRC,
28 1992). Appendix E, Section E.1, of Volume 1 of this NUREG describes the values
29 recommended for use in the screening models developed for application to decommissioning.
30 Specifically, Table E.6 gives inhalation (i.e., solubility) class and the f_1 factor for each
31 radionuclide. Because the values are recommended for screening analyses, in most cases, the
32 solubility class selection will maximize the potential inhalation dose. For plutonium, the solubility
33 class represents the most common chemical form that will likely be encountered in
34 environmental situations. For the other radionuclides, the solubility classes and gastrointestinal
35 uptake fractions are defined for the combination resulting in the highest dose.
36

37 The licensee should use a consistent dose methodology for all the applicable performance
38 objectives (i.e., for the performance assessment (10 CFR 61.41), intruder assessment (10 CFR
39 61.42), and assessing doses during operations (10 CFR 61.43)). If the licensee wishes to use a
40 methodology not consistent with the definitions in 10 CFR Part 20, they may request an
41 exemption from the definition of "weighting factor" as defined in 10 CFR 20.1003. For example,
42 the licensee could request to use (1) the latest dose conversion factors (e.g., ICRP
43 Publication 72, "Age-Dependent Doses to the Members of the Public from Intake of
44 Radionuclides, Part 5, Compilation of Ingestion and Inhalation Coefficients," issued
45 September 1996 (ICRP, 1996), or (2) EPA-402-R-99-001, Federal Guidance Report No. 13,
46 "Cancer Risk Coefficients for Environmental Exposure to Radionuclides," issued

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

4
5 Licensees must select organ dose weighting factors and corresponding dose factors (i.e.,
6 extrapolation of the dose to a specific organ to the effective dose to the whole body) that were
7 developed using the same dose methodology. For example, if a licensee uses the organ dose
8 weighting factors specified in 10 CFR 20.1003 that were developed from the ICRP 26 dose
9 methodology (ICRP, 1977), they should use the corresponding dose factors that are tabulated in
10 FGR Report 11 and ICRP Report 30 (ICRP, 1979; ICRP, 1980; ICRP, 1982). If a licensee uses
11 the organ dose weighting factors that were developed from the ICRP 60 dose methodology
12 (ICRP, 1991), they should use the corresponding dose factors that are tabulated in FGR Report
13 13 and ICRP Report 72. A licensee should not select organ dose weighting factors from
14 10 CFR 20.1003 and dose factors from ICRP Report 72, because they were not calculated
15 using consistent dose methodologies.

16
17 Licensees should provide justifications for age-based considerations of scenarios, *critical group*
18 assumptions, and the chemical forms, consistent with the dose methodology system being
19 used. Age-based considerations should evaluate the sensitivity to the total dose, rather than
20 specific pathways.

21
22 If a licensee chooses to modify their existing performance assessment and intruder analyses
23 based on the availability of new dosimetry information, the licensee will need to submit the
24 updated performance assessment and intruder analysis for review and approval, similar to any
25 other update (see Section 8.0). As stated previously, the licensee may need to request an
26 exemption to 10 CFR Part 20 to use the latest dose conversion factors to perform dose
27 analyses for individuals during operations to meet the 10 CFR 61.43 performance objective.

28 **2.3 Assessment Context**

29 **2.3.1 Context of the Performance Assessment**

30
31 The first step in the performance assessment process is the assessment context. In order to
32 develop the context of a performance assessment a licensee should answer the following
33 questions:

- 34
35 What is being assessed?
36 Why is it being assessed?
37 What is the scope of the assessment?

38
39 Components of an assessment context can comprise the assessment purpose, regulatory
40 framework, assessment end points, assessment philosophy, waste characteristics, disposal
41 system characteristics, and assessment timeframes. For LLW, the regulatory framework is

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

1 found in 10 CFR Part 61, including the performance objectives found in Subpart C. However,
2 the purpose of conducting a performance assessment may vary. The licensee should consider
3 the audience for the performance assessment results. Different strategies for the performance
4 assessment may be used (e.g., conservative vs. realistic, simple vs. complex, deterministic vs.
5 probabilistic). A well-defined assessment context can be used to determine the level of model
6 abstraction, as well as data and computational needs. For example, if the assessment context
7 calls for a simple modeling approach, a relatively simple mathematical model abstracted from
8 the conceptual model may be sufficient. In addition, the assessment context may provide a
9 comparison point to other performance assessments. For example, if a similar site has been
10 modeled by another organization, a comparison, and any possible discrepancies, of the model
11 outputs will be easier to understand. For a description of an assessment context as it pertains
12 to biosphere models for geologic disposal, the BIOMASS program, as documented in IAEA
13 (2003), provides information and guidance.

14 **2.3.2 Approach to Different Timeframes**

15
16 This section of the guidance document describes the information that a licensee should provide
17 and a reviewer should evaluate with respect to the timeframe for the analyses for the intruder
18 assessment, performance assessment, and stability assessment for the compliance period,
19 protective assurance period, and the performance period.

20
21 When completing technical analyses, the licensee should select the period of time over which
22 the potential future behavior of the disposal system will be evaluated against the performance
23 objectives; this period of time is termed the “*analysis timeframe*.”

24
25 Licensees conduct performance assessments to understand how a waste disposal system may
26 perform with respect to limiting releases to offsite members of the public. Performance
27 assessments are also used by stakeholders to understand the potential impacts of
28 uncertainties. Numerous sources of uncertainty are associated with projecting the future
29 radiological risks from waste disposal for thousands of years, including, but not limited to,
30 natural, engineering, and societal sources. Section 2.2.2 discusses the types of uncertainties
31 that are commonly explicitly considered in technical analyses by licensees or reviewers.

32
33 One of the outputs of technical analyses for LLW disposal is the projected dose to a member of
34 the public from radioactivity released to the environment. The projected doses are compared to
35 regulatory requirements and the regulator determines whether there is an acceptable degree of
36 confidence that the dose is consistent with the regulatory limit. In the NRC’s terminology, that
37 degree of confidence is described as “reasonable assurance.” The results of a compliance
38 analysis should not be interpreted as unequivocal proof of the expected behavior of a waste
39 disposal facility, because of the uncertainties associated with the projected radiological risk over
40 long time periods. Over extended periods of time, uncertainties associated with the
41 performance of natural and engineered systems may increase, and uncertainties associated
42 with human behavior definitively increase. In some cases, unmanageable uncertainty may be a
43 suitable reason not to dispose of waste if the consequences have unacceptable outcomes
44 (represented in that uncertainty). The technical analyses supply information to inform decision-
45 makers and the public.

46
47 A three-tiered approach to the analyses timeframe is specified in 10 CFR Part 61. When
48 implemented properly, the three-tiered approach should accomplish the main goal of licensees

1 communicating the near- and long-term risks in an appropriate uncertainty context to regulators
2 and other stakeholders. For discussion purposes in this guidance document, these phases are
3 defined as follows:

4
5 *Analysis timeframe* — The timeframe over which a licensee should assess the projected
6 performance of the disposal facility while factoring in the characteristics of the waste,
7 engineered barriers, disposal site, and associated uncertainties. The analysis timeframe is
8 divided into three phases: a compliance period, a protective assurance period, and a
9 performance period. However, the performance period is only applicable when certain
10 conditions are met, and therefore, it may not apply to some sites.

11
12 *Compliance period* — The period of time over which a licensee must demonstrate with
13 reasonable assurance that the disposal facility will meet the performance objectives found in
14 10 CFR 61.41(a), 10 CFR 61.42(a), and 10 CFR 61.44. A quantitative assessment should be
15 performed. The compliance period is defined to be 1,000 years.

16
17 *Protective assurance period* — The period from the end of the compliance period through
18 10,000 years following closure of the site. A licensee must demonstrate that releases to the
19 environment and exposures to an inadvertent intruder have been minimized below 5 mSv (500
20 mrem) or to a level that is supported as reasonably achievable based on technological and
21 economic considerations. Licensees should perform quantitative analyses for the protective
22 assurance period (see Section 6.0).

23
24 *Performance period* — The period of time over which a licensee evaluates the ability of the
25 disposal system to contain long-lived waste and demonstrates that releases are minimized to
26 the extent reasonably achievable (discussed in Section 7.0). The performance period begins at
27 the end of the protective assurance period and extends as long as necessary to demonstrate
28 that the metric of the performance period can be met. Licensees should perform a quantitative
29 assessment, though uncertainties may be large, which may decrease the confidence that a
30 licensee should place in the results of the analyses. A qualitative interpretation of the
31 quantitative results by the licensee is appropriate in most cases.

32 **2.3.2.1 Compliance Period**

33
34 10 CFR 61.2 specifies a period of 1,000 years as the timeframe over which a licensee must
35 demonstrate compliance with the quantitative limits and stability requirements of Subpart C
36 (10 CFR 61.41(a), 10 CFR 61.42(b), and 10 CFR 61.44). Licensees should conduct a
37 performance assessment, intruder assessment, and site stability evaluation for the compliance
38 period. A quantitative assessment of disposal facility performance should be developed
39 covering the timeframe of the first 1,000 years following closure of the disposal facility. The
40 quantitative assessment may also be risk-informed. The waste characteristics (e.g., the amount
41 of short- and long-lived wastes), complexity of the disposal facility design, and complexity of the
42 disposal site and surrounding environment will influence the level of detail that should be
43 provided to support the technical analyses (see Example 2.1).

Example 2.1: A facility is expected to receive typical LLW generated by commercial entities (e.g., limited concentrations of long-lived waste). The waste has average concentrations of long-lived radionuclides at or below one-tenth of the values listed in Table 1 of 10 CFR 61.55. Additionally, the facility is expected to receive waste with long-lived radionuclides that are not found in Table 1 of 10 CFR 61.55 and are at concentrations less than the natural soils surrounding the facility.

Conclusion: A performance assessment, intruder assessment, and stability assessment should be completed to demonstrate compliance with 10 CFR 61.41(a), 10 CFR 61.42(a), and 10 CFR 61.44. Because the waste is dominated by short-lived activity and long-lived concentrations are limited, specialized models and associated model support for long-term processes (e.g., cycling of climate) are not necessary.

1

2 **2.3.2.2 Protective Assurance Period**

3

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

18

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

28

29 A licensee could demonstrate that a facility accepting only short-lived waste could meet the
30 regulatory requirements without a quantitative assessment of the impacts extending many
31 thousands of years into the future. The performance assessment for a facility that accepts large
32 quantities of long-lived waste would need to consider FEPs that could significantly affect
33 whether the facility could meet the performance objectives for the protective assurance period,
34 and this set of FEPs may be more extensive than that associated with the disposal of short-lived

1 waste. Disposal of large quantities of long-lived waste will likely require a performance
2 demonstration by a licensee that is much more complex than the evaluation of the disposal of
3 short-lived waste. The demonstration of performance for the disposal of long-lived waste will
4 likely require significantly more resources to complete.
5

6 Licensees and regulators should consider if radiological risk from long-lived waste is being
7 limited by the waste characteristics or by the facility design and site characteristics. If the risk is
8 limited by the waste characteristics (e.g., limited inventory) a long-term quantitative analysis
9 may not be necessary. If the risk from long-lived waste is limited by the facility design and site
10 characteristics, then a long-term quantitative assessment should be developed. It is appropriate
11 for a licensee to use simplified calculations to determine the detail needed for the longer term
12 assessment, as long as the simplified calculations are based on reasonably conservative
13 scenarios and models (see Example 2.2). In other words, the NRC staff expects the process of
14 determining the level of detail that may be needed for a longer term assessment to be iterative.
15 In addition, a licensee should consider waste characteristics for the full protective assurance
16 period to account for the potential ingrowth of long-lived progeny when estimating the
17 concentrations of long-lived radionuclides in the disposed waste.
18

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

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

20 **2.3.2.3 Performance Period**

21
22 The performance period is the time after the protective assurance period when longer-term
23 doses could result from the disposal of certain types of long-lived waste. The objective of
24 analyses provided for the performance period is for a licensee to demonstrate that releases
25 from long-lived waste disposed of in the facility have been minimized to the extent reasonably
26 achievable and that the facility has been designed with consideration of the potential long-term
27 radiological impacts, consistent with available data and current scientific understanding. The
28 analyses should identify the features of the design and site characteristics that will reduce long-
29 term impacts and describe the capabilities of these features. Analyses for long-lived waste
30 should provide the range of peak annual doses that are projected to occur after 10,000 years

1 following site closure, or other metrics such as concentrations of radioactivity in the environment
2 and flux rates to the environment. The long-term performance period analyses are designed to
3 complement the technical analyses performed for the compliance demonstration and protective
4 assurance analyses (10 CFR 61.13(a), (b), (d), and (f)).
5

6 As described below, and in more detail in Section 7.0, a number of approaches are acceptable
7 for providing the necessary information for performance period analyses. A licensee should
8 provide sufficient information and analyses for the long-term performance period that
9 demonstrate that the 10 CFR 61.41(c) and 10 CFR 61.42(c) performance objectives will be met.
10 The licensee should use available data and current scientific understanding to assess the
11 long-term performance of the waste disposal facility, including uncertainties.
12

13 The NRC staff recommends the performance period analyses should cover the period of
14 geologic stability at the disposal site, limited to a maximum of one million years or the peak
15 dose² considering uncertainty, whichever comes first. It would not be appropriate to constrain
16 the analyses to the period of near-surface geologic stability, as one of the reasons for
17 undertaking the performance period analyses is for a licensee to communicate to decision-
18 makers the potential range of consequences from the disposal action. Near-surface geologic
19 instability may result from a process such as fluvial erosion (e.g. driven by lake formation),
20 which could have severe impacts at an unstable site. Near-surface geologic instability may
21 indicate that the site is unsuitable for disposing of significant quantities of long-lived radioactive
22 waste. A licensee should not use near-surface geologic instability as a basis for limiting the
23 analysis. If the analysis for LLW disposal was limited to the period of near-surface geologic
24 stability, the analysis could be truncated prematurely and the long-term risks and uncertainties
25 may not be understood. In addition, instability could be used as a basis to select a site, which is
26 not acceptable. Section 7.0 provides more detail on specific technical issues that may be
27 relevant to technical analyses for the performance period.

28 **2.3.2.4 Site Characteristics**

29
30 Site characteristics are identified in 10 CFR 61.50 that either must be avoided or must be
31 present at a proposed disposal site. As described in the concepts section (10 CFR 61.7), a
32 licensee needs to consider site characteristics in terms of the indefinite future, taking into
33 account the radiological characteristics of the waste. They should evaluate site characteristics
34 for at least a 500-year timeframe and understand that the interpretation of the indefinite future is
35 different for different types of waste. Flexibility is provided to licensees to ensure that they can
36 consider site characteristics in a risk-informed manner. The site suitability requirements are
37 designed to be applied to ensure that the long-term performance objectives of Subpart C are
38 met. A cornerstone of radioactive waste disposal is the stability of the disposal system. Sites
39 for which the site characteristics requirements cannot be satisfied are unlikely to meet this
40 primary regulatory objective.
41

42 For the disposal of any type of waste, the hydrological site characteristics identified in
43 10 CFR 61.50 are required³ for the next 500 years. For example, disposal should not be

² As discussed in Section 7.0, the performance period analyses may include metrics other than dose (e.g., concentration, fluxes). See Section 7.0 for more detail.

³ 10 CFR 61.50 lists the hydrological characteristics a site is required to have as well as other hydrological characteristics a site must not have.

1 permitted at a site where the facility is expected to be in the 100-year floodplain over the next
2 500 years. 10 CFR 61.50(a)(4) specifies other characteristics of the site that should not be
3 present at any timeframe because they significantly affect the ability of the disposal site to meet
4 the performance objectives of Subpart C (e.g., population growth, tectonic processes).
5 Appendix B presents currently understood hazard maps related to the features and phenomena
6 of the 10 CFR 61.50 criteria.

7
8 Whether a licensee's consideration of site characteristics needs to be extended to the end of the
9 protective assurance period (i.e., 10,000 years) or into the performance period depends on the
10 type of waste that will be disposed. For a disposal facility that only accepts short-lived waste
11 and also contains minimal quantities of long-lived waste, a licensee's consideration of the site
12 characteristics over the next 500 years would ensure that a proper site has been selected and
13 that it would be capable of being characterized, modeled, analyzed, and monitored. A licensee
14 is not prohibited from considering site characteristics for more than 500 years, and it may
15 enhance the robustness of their technical evaluation. However, a consideration of site
16 characteristics for more than 500 years for the disposal of waste with limited long-lived
17 radioactivity would be unnecessary. To determine if the amount of waste a licensee wishes to
18 dispose of is a minimal quantity, a licensee may simply calculate the product of the projected
19 facility volume (or mass) and the concentrations provided in the table in 10 CFR 61.13(e), then
20 apply the sum of the fractions rule for mixtures of radionuclides described in
21 10 CFR 61.55(a)(7). In this context, a minimum quantity is defined as the product of volume
22 and concentration of waste that corresponds to a sum of fractions of one tenth.

23
24 The timeframes that reviewers should use to evaluate the site characteristics requirements are:

- 25
26 A) If $C < 1/10^{\text{th}} X \iff$ evaluate 500 years
27 B) If $1/10^{\text{th}} X < C < X \iff$ evaluate 10,000 years
28 C) If $C > X \iff$ evaluate performance period

29
30 where C is the disposal site waste concentration sum of fractions for long-lived waste, and X is
31 the 10 CFR 61.13(e) Table A sum of fractions. By providing a value for long-lived alpha-
32 emitting radionuclides in Table A, most isotopes of concern (including uranium isotopes) will be
33 considered using this approach. However, in some circumstances a disposal facility's inventory
34 may contain other long-lived isotopes. If there are long-lived isotopes that are observed to be
35 key contributors to projected risk that are not included in Table A (e.g. Cl-36), a licensee should
36 evaluate the site characteristics over a timeframe as long as necessary to support the relevant
37 performance demonstration. In most cases the licensee would have performed this iterative
38 evaluation (from characterization to performance analyses and back to characterization) prior to
39 submittal of the analyses to the regulator.

40 **2.4 System Description**

41
42 The second step of the performance assessment process is for the licensee to describe the
43 LLW disposal system and the natural environment of the site. The objective of the system
44 description review is to ensure that the information that was used to develop the performance
45 assessment models and the information describing the overall disposal system have been
46 adequately described. The description should be adequate to allow an independent reviewer to

1 understand the LLW disposal system. The system description should provide, at a minimum,
2 information describing:

- 3
- 4 • The site;
- 5 • The natural setting;
- 6 • The disposal facility;
- 7 • The interaction of the site and disposal facility;
- 8 • The waste to be disposed of including its radiological, chemical, and physical
9 characteristics;
- 10 • Potential disruptive processes; and
- 11 • The characteristics of members of the public potentially affected by the facility.
- 12

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

18 **2.5 Scenario Development**

19

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

27

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

32

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

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

11
12 Scenarios are often assembled and classified based on their likelihood of occurrence. For
13 example, the terms “central,” “base case,” or “nominal” scenarios are often used to describe the
14 expected future state of the system. “Altered evolution” or “alternative” scenarios are typically
15 considered less probable but still plausible, while implausible “what if” scenarios may be used to
16 explore the robustness of the system. “Stylized scenarios” may be used to represent future
17 human actions. Receptor scenarios are subsets of scenarios and describe the end process by
18 which people may become exposed to radiation. A residential farmer receptor scenario, for
19 example, is a general description of the pathways leading to possible exposure and of the
20 behavior and lifestyle of the hypothetical receptor. The relationship between scenarios and
21 receptor scenarios is discussed further in Section 2.2.4.1.

22
23 A *safety function* is defined qualitatively as a function through which a component of the
24 disposal system contributes to safety and achieves its safety objective throughout the analysis
25 timeframe. Safety functions are used in the top-down approach to scenario development.

26
27 Often, performance assessments will exclude scenarios from the base case based on the
28 scenario development process but will evaluate scenarios called “what if” scenarios. These
29 “what if” scenarios include scenarios of varying likelihood – some may be plausible whereas
30 others are extremely unlikely. Many “what if” scenarios originate from specific concerns
31 expressed by stakeholders. They can include very conservative scenarios that would normally
32 have been rejected in a scenario development process due to very low probability of occurring
33 or low impact on the results. If stakeholder interest is very high, scenarios that are usually
34 excluded during the scenario development process could still be included in the performance
35 assessment analyses; however, these scenarios would usually be labeled as very unlikely to
36 occur and would not be considered as a valid alternative scenario by the analysts. With “what
37 if” scenarios, distinctions between likely and very unlikely scenarios are not made since they
38 were constructed outside of the scenario development process. As a consequence, the
39 interpretation of the results may be difficult since it is not clear which results are realistic and
40 which ones are very unlikely. Commonly in these cases, all the results are discussed; however,
41 they are not included in the decision-making process since the results are considered unrealistic
42 (even though some of the scenarios may have been valid alternative scenarios of future
43 conditions and events). Therefore, it is generally recommended that licensees avoid “what if”
44 type scenarios and complete the full scenario development process. If “what-if” scenarios are
45 used, a qualitative or quantitative likelihood of the scenario should be developed to provide
46 context for the results.

47

2.5.1 Scope of Analysis

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

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

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

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

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

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

1 screening process. Example 2.3 provides some guidance on determining whether a site is
2 simple or complex.

3
4 Lists for FEPs (FEPs lists are discussed in Section 2.5.3.1.1; a generic FEP list for LLW
5 disposal is found in Appendix C) can be quite extensive. Some amount of aggregation may be
6 necessary to make the screening, assessment, and implementation process manageable. On
7 the other hand, lists that are too general will not be useful, as key FEPs may not be included at
8 the implementation stage or may not be included with appropriate responses and functional
9 behavior because of the coarseness of their definition. The licensee should consider whether
10 inclusion of the FEP at the next level of detail would improve the assessment of system
11 performance. In either case, a licensee should demonstrate that the FEPs included in the
12 analysis are sufficiently comprehensive. Because LLW disposal has been performed at facilities
13 throughout the world, the licensing and operational experiences of other disposal facilities can
14 provide a good starting point for licensees at a new facility.
15

Example 2.3: Is my site simple or complex?

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

16
17 The analyses required to develop scenarios are closely linked with conceptual model
18 development and model abstraction. FEP screening and scenario development are increasingly
19 used as a means to build confidence in the scope of a performance assessment. The more
20 complete the licensee's analysis, the more likely they will be able to gain confidence from the
21 reviewers and stakeholders. When a licensee develops scenarios, the scenarios can be used
22 to focus stakeholder attention on the key technical issues. Scenarios provide an important area
23 for communication among various stakeholders and an opportunity to discuss and reach a
24 consensus on areas of specific importance. Licensees can discuss their use of scenarios and
25 provide a rich and accessible means for public involvement.
26

27 One of the main purposes of FEP screening and scenario development for a radioactive waste
28 disposal system is to use scientifically-informed expert judgment to guide the development of
29 descriptions of the disposal system and its future behavior. Scenario uncertainty is handled
30 directly by describing alternative future states of the system and by allowing for a mixture of
31 quantitative analysis and qualitative judgments; however, it is not an attempt to predict the
32 future. The aim is to investigate the importance of particular sources of uncertainty and provide

1 meaningful illustrations of future conditions to assist in the decision-making process (NEA,
2 2001).

3 **2.5.2 Role of Qualified Specialists**

4
5 The technical basis for FEPs screening and the approach to scenario formation depends to a
6 significant extent upon the judgment of the individuals performing the study. The completeness
7 of a FEPs analysis can be enhanced by including a broad range of people and diverse sources
8 of information. It is usually better to identify and categorize a range of broadly-defined FEPs to
9 ensure comprehensiveness of the FEP process. If appropriate expertise is not available
10 internally, a licensee may need to seek the input from experts external to their organization (i.e.,
11 professionals in the field of concern such as hydrogeologists, geomorphologists, seismologists,
12 chemists, etc.). Licensees should obtain information from different sources, a variety of
13 methods, and from all relevant disciplines. Licensees should document decisions based on
14 expert judgment. The qualifications of the analysts performing the FEPs screening are also
15 very important.

16 **2.5.3 Approaches**

17
18 There are several methods that can be used by licensees to identify FEPs, screen FEPs, and
19 construct scenarios. A licensee should ensure that the process is systematic, comprehensive,
20 logical, traceable, and transparent. Different approaches to scenario formation include bottom-
21 up, top-down, and a mixture of the two.

22
23 In bottom-up scenario formation, the screened FEPs are combined to form a limited number of
24 scenarios for consequence analysis. Sandia National Laboratory developed a structured
25 approach to scenario selection for the NRC (NRC, 1993a). Initially, this approach was applied
26 for disposal of HLW, but was later expanded to disposal sites for other radiological *source*
27 *terms*. When using a bottom-up approach, the licensee should develop a comprehensive list of
28 FEPs as a starting point. Development of a comprehensive list typically involves the use of
29 generic FEPs lists and the identification of other site-specific FEPs. This is followed by a
30 screening process to exclude certain FEPs from further consideration. The retained FEPs are
31 combined into scenarios for evaluation. FEPs screening criteria may include prohibition by
32 regulation, low probability, or limited consequence. The scenario in which disruptive events do
33 not occur is usually identified as the central scenario and represents a continuation of the
34 estimated present day undisturbed conditions. However, in some cases the central scenario
35 could include disruptive processes if they are expected in the normal future evolution of the site.
36 The projection of present day conditions into the future may include dynamic effects. In other
37 words, a licensee should not interpret 'undisturbed' as 'static'. For example, degradation of
38 engineered barriers may be part of a central scenario.

39
40 In the top-down approach, licensees develop scenarios based on analyses of how the safety
41 functions of the disposal system may be affected by possible events and processes. First, the
42 licensee should identify the safety functions of the waste disposal system and then consider the
43 combination of conditions that could affect one or more of the safety functions. The top-down
44 scenario development approach used in the assessment of HLW disposal consisted of iterative
45 steps and is described in detail in NEA (1992). While the NEA (1992) document may serve as
46 an example of the process, a lower level of effort should be appropriate for LLW disposal.
47

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

7
8 Regardless of the method used for developing the scenarios, phenomena and barrier
9 components that could significantly influence the performance of the disposal system should be
10 addressed in the assessment. Hence, a licensee should show that potentially significant
11 transport pathways have been considered and that possible evolutions of the disposal system
12 have been taken into account. Licensees should give specific consideration to events that could
13 occur repetitively during the assessment timeframe (e.g., droughts, floods, and earthquakes).
14 They should consider the performance of the disposal system under both present and future
15 conditions.

16
17 All of the methodologies share the same basic approach, namely that a central scenario is
18 considered a starting point. A licensee should demonstrate that relevant FEPs have been taken
19 into account when developing alternative scenarios. Alternative scenarios are generally less
20 likely than the central scenario. Alternative scenarios can be developed on the basis of
21 disturbances to the normal evolution of the disposal system or to represent different amounts of
22 degradation of the safety functions. If uncertainty is high, it may be difficult to classify different
23 scenarios as central or alternative.

24
25 A licensee should explain and justify which scenarios are regarded as representing the
26 expected evolution of the system, and which scenarios address FEPs having an unlikely
27 probability of occurrence. The range of future physical environmental conditions at the site and
28 the range of potentially exposed groups should be identified. Licensees and regulators usually
29 assume that humans will be present and that they will make use of local resources. It is
30 appropriate for licensees to assume that humans in the future will have similar habits to present
31 humans, except where this is clearly inconsistent with the assumed variations in climatic
32 conditions at a site. Section 2.2.4.2 provides additional guidance to licensees on the
33 development of receptor scenarios.

34
35 If disruptive events are represented in a probabilistic performance assessment model, a
36 licensee should conservatively assign the probabilities of an event occurring if the frequency of
37 the event is not known. Formal expert elicitation may be necessary to define event frequencies.
38 Alternatively, the licensee may represent a range of scenarios to capture the potential effects of
39 disruptive events, without weighting the potential scenarios with probabilities. Some
40 understanding of the likelihood and frequency of disruptive events is still likely to be necessary
41 for decisionmakers, unless the dose projections resulting from the evaluation of disruptive
42 events are below regulatory limits. Section 2.2.3.1 provides additional information of expert
43 elicitation.

1 **2.5.3.1 Bottom-Up Approach**

2 2.5.3.1.1 *Identification and Categorization of FEPs*

3
4 A large number of FEP lists, catalogs, and databases have been developed in different
5 countries and encompass a range of radioactive *waste types*, disposal system designs, and
6 geological environments. The size of these FEP lists varies, as do the content and level of
7 detail of entries. A listing of international published FEP lists, catalogs, and databases have
8 been compiled by NEA (2002). Licensees should perform a literature search when developing
9 their scenario analyses because FEP lists continually change as scientific information is
10 developed. Licensees may want to consider the generic FEP list for LLW disposal that the NRC
11 staff developed in Appendix C of this document.

12 2.5.3.1.1.1 Identification and Categorization of Present FEPs

13
14 In order for a licensee to identify FEPs important to LLW disposal at their site, they should
15 review existing FEP lists. The first step in the identification and categorization process consists
16 of reviewing the information provided by the assessment context, as it relates to the
17 performance assessment of the site. For example, legislation or regulatory guidance may
18 predetermine some individual or categories of FEPs that a licensee should consider (e.g., future
19 human activity, the biosphere system, or the future climate states). A licensee could use a
20 previously compiled generic FEPs list as a starting point to save time and effort. They will need
21 access to information and documents pertaining to the characterization and description of the
22 site being considered.

23
24 The identification and categorization process may be iterative. Initially, the licensee may identify
25 and categorize the FEPs assuming the site has static conditions. Often the central scenario can
26 be constructed from present FEPs if the proposed disposal site is in an area of geological and
27 geomorphological stability. Next, dynamic conditions such as natural degradation processes
28 are assumed to affect the natural and engineered barriers. This approach is described in the
29 following steps:

- 30
31 (1) Use a generic list to identify features and processes that are currently present. For this
32 step, features or processes likely to be there in the future or that existed only in the past
33 should be temporarily set aside until the next phase, as discussed in Section 2.5.3.1.1.2.
- 34 (2) Eliminate features and processes in Step 1 that have no potential to affect performance.
- 35 (3) Add features and processes that have occurred relatively recently (i.e. within 100 years);
36 not events that have occurred in the long distant past (e.g., glaciers) or that may occur in
37 the long-term future (these will be identified later as discussed in Section 2.5.3.1.1.2).

38
39 The identification step is followed by, and closely linked to, the categorization step whereby
40 FEPs with certain similar properties are grouped together. Categorization provides a framework
41 for organizing the scenario development process and the subsequent assessment. In addition,
42 it provides information on interactions and interrelationships between FEPs. The primary
43 objective is to uncover missing factors, therefore, categories that examine the system from
44 different viewpoints should be used (NEA, 1992).

45
46

- 1 Examples of categorization include:
2
3 • Dividing FEPs related to either natural, human, or waste into separate categories;
4 • Providing categories according to the time scale during which different events and
5 processes occur;
6 • Providing categories of FEPs related to either near-field, far-field, or biosphere;
7 • Categorizing FEPs according to combinations of different magnitudes of the probability
8 and the consequence; and
9 • Classifying according to scientific discipline.

10 2.5.3.1.1.2 Identification and Categorization of Future FEPs
11

12 In the previous section, the NRC staff suggested that a licensee obtain the first FEP list by
13 assuming the proposed disposal site is not intrinsically dynamic. However, the NRC staff
14 recognizes that most proposed disposal areas are dynamic (e.g., shifting wind deposition and
15 erosion). Each disposal site will be in its own state of equilibrium or disequilibrium. Most sites
16 are chosen because the area is close to equilibrium (i.e., in an area of geological and
17 geomorphological stability). Events that do occur may be limited in scope, and therefore, are
18 unlikely to have a significant impact on performance of the proposed site.
19

20 For some sites, a few hundred years may be sufficient to result in significant changes to the
21 disposal site, which would make use of a present-day FEP list incomplete. Changes can occur
22 over different temporal and spatial scales. Some, such as the clearance of woodland and its
23 replacement by farmland, might occur over relatively short timescales. Others, such as the
24 closing of open water bodies by the deposition of sediments and changes to the topographical
25 landscape, may occur over longer timescales and can be considered to be gradual processes.
26

27 The NRC staff suggests that a licensee continue the identification process after the completion
28 of the steps listed in the previous section. Features and processes should be identified that
29 may occur during the analysis timeframe based on documentation and studies of the past
30 natural history of the area. Processes identified should include processes that are expected to
31 occur over the entire time period of interest (e.g., leaching, dissolution, fracturing). The analyst
32 or *qualified specialist* should always be aware that this step is for the purposes of identification
33 and categorization of potential FEPs; systematic screening of FEPs occurs in the subsequent
34 step. Some processes may have slow to moderate rates but may be episodic in nature. It
35 would be appropriate for a licensee to consider episodic processes if the effect of the process
36 on the disposal system could be significant.
37

38 A licensee can identify future FEPs through a qualitative exercise that should not necessarily
39 involve original research or an effort that would take an extended time to complete; however, it
40 will require the time of qualified specialists and may involve literature searches. Examination of
41 past local natural history can often result in the identification of processes that may have been
42 relevant at a site in the past and could be an indicator of potential future behavior. This past
43 history can be used as a basis to identify and categorize a FEP for further consideration. For
44 example, a present day desert environment may have had higher average annual precipitation
45 rates in the past with a higher density of rivers and lakes (e.g., Lake Manly covering Death
46 Valley in the past) and different distributions of fauna and flora. If the past environment is

1 considered plausible in the future for the analysis timeframe considered, the associated FEPs
2 from this past environment would be used as a basis to identify and categorize a FEP for further
3 consideration. Some of the FEPs from the present will persist in the future, however, some
4 processes may stop (e.g., groundwater recharge due to permafrost) and other features may
5 appear (e.g., a forest which was previously scrubland).

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

13 2.5.3.1.2 Systematic Screening of FEPs

14
15 A licensee should perform systematic screening of identified FEPs and should determine the
16 subset of FEPs important to disposal system performance, documenting the basis for excluding
17 or including a FEP for further consideration. A licensee should use clear and justifiable criteria.
18 Screening approaches can vary from using some type of 'importance' ranking scale (e.g., 0
19 through 10), or simply an 'include' or 'exclude' system. Exhaustive analysis of importance is not
20 necessary for FEP screening for LLW disposal. Simple calculations or bounding estimates can
21 assist with the selection. Licensees should document the assumptions, data, or empirical
22 information used to make these determinations. They should perform the screening process on
23 a site-specific basis, and evaluate FEPs or FEP categories one at a time against a screening
24 criterion. During the screening process, interactions between FEPs should be considered. If
25 there are uncertainties as to whether a FEP can be screened, then it should be retained. The
26 FEP can be reevaluated at a later stage in the screening and evaluation process.

27
28 The following subsections discuss various aspects of screening of FEPs. The regulatory aspect
29 is considered first since these screening criteria are legal in nature and take precedent over
30 other screening considerations.

31 2.5.3.1.2.1 Regulatory

32
33 FEPs can be screened out based on inconsistency with applicable regulations. The NRC
34 approach to analyzing timeframes is based on a compliance period of 1,000 years, a protective
35 assurance period through 10,000 years following closure of the disposal site, and a
36 performance period of undefined duration during which a licensee must demonstrate that effort
37 has been made to minimize releases to the extent reasonably achievable. The performance
38 assessment should reflect changes in FEPs of the natural environment such as climatology,
39 geology, and geomorphology. The scope of the FEPs considered does not need to be
40 expanded unless information is available to do so.

41
42 Section 10 CFR 61.50 is an important regulation that affects the FEPs screening process, as it
43 provides the disposal site suitability requirements for the land disposal of LLW. The process to
44 determine if some of these criteria will be met is complementary to the FEPs process. The
45 criteria from 10 CFR Part 61.50 associated with the process of FEPs analysis are
46 10 CFR 61.50(a)(2)(i-iv), 10 CFR 61.50(a)(3) and 10 CFR 61.50(a)(4)(ii-iv).

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

4
 5 Site suitability requirements are treated differently in 10 CFR Part 61 depending on the type and
 6 timeframe. Historically, hydrological FEPs were the key drivers of poor performance of early
 7 (pre-10 CFR Part 61) LLW disposal facilities. Therefore, hydrological characteristics of the site
 8 are treated differently from other site characteristics. Regardless of the type of waste disposed,
 9 the hydrological site characteristics are either required to be present for disposal for the
 10 500-year timeframe (e.g., the site must be generally well-drained) or should not be present for
 11 the 500-year timeframe because they will adversely affect the performance of the disposal site
 12 (e.g., waste may not be disposed of in the zone of water table fluctuation).

13
 14 After the 500-year timeframe, the evaluation of hydrological site characteristics can consider the
 15 impact of the characteristics on a licensee's ability to demonstrate that the Subpart C
 16 performance objectives would be met. Disposal systems with water challenges in the present
 17 day and foreseeable future are not amenable to stability and defensible modeling and
 18 assessment. Table 2-1 provides the analyses that should be completed for the disposal site
 19 suitability requirements in 10 CFR 61.50 that are not excluded based on FEP screening.

20
 21 **Table 2-1 Analyses Required for Included FEPs Based on 10 CFR 61.50**

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

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

24 ² The stability analyses for included non-hydrologic FEPs may be based on demonstrating that the
 25 10 CFR 61.41 and 10 CFR 61.42 performance objectives will be met.
 26
 27

1 **Screening of FEPs Based on the Requirements in 10 CFR 61.50**

2 **10 CFR Part 61.50(a)(4)(ii):** *Areas must be avoided having known natural resources*
3 *which, if exploited, would result in failure to meet the performance objectives of*
4 *Subpart C of this part.*

5 Categories of FEPs should be reviewed for known natural resources (i.e., for natural material
6 currently considered to be a resource and whose range and scope is currently known).
7 Calculations or estimates on the adjustment in value of a natural resource beyond a decade are
8 not required. If review of the FEPs determines that natural resources of the type described in
9 10 CFR Part 61.50(a)(4) exist near a proposed disposal site and are likely to be exploited,
10 resulting in failure to meet the performance objectives of Subpart C, then the site is not qualified
11 for LLW disposal.

12
13 The NRC staff recommends that a future licensee survey and evaluate an area for potentially
14 exploitable natural resources within a radius of five kilometers from the future boundary of a
15 land disposal facility. For potential disposal sites located within valleys or in a riparian setting, a
16 licensee should consider surveying and evaluating further than five kilometers in the upstream
17 direction since gravitational forces on air, water, and materials may allow disruptive influences
18 from the exploitation of natural resources to travel greater distances downstream.

19
20 **10 CFR Part 61.50(a)(2)(i):** *Waste disposal shall not take place in a poorly drained site*
21 *or a site subject to flooding or frequent ponding, or in a 100-year flood plain, coastal*
22 *high-hazard area or wetland, as defined in Executive Order 11988, "Floodplain*
23 *Management Guidelines".*

24
25 A licensee must demonstrate that the disposal site is not located in a projected 100-year
26 floodplain or a permanent or periodic wetland for a period lasting 500 years after
27 closure. Section 2.4.1, Appendix A in NUREG-1200 provides additional guidance. For the
28 ensuing period beginning 500 years after closure of the disposal site the licensee may, in
29 accordance with 10 CFR 61.50(a)(3), demonstrate that the condition will not exist or that the 10
30 CFR 61.41 and 10 CFR 61.42 performance objectives can be met irrespective of the
31 condition. There are two main geomorphic zones to consider: (i) coastal areas, and (ii) flood
32 plains and wetlands.

33
34 Coastal Areas

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

39
40 *Vulnerability to Erosion:* Possible FEPs that could cause detrimental erosion rates include
41 increased rainfall and/or an increased gradient (and therefore, an increase in the erosional
42 power of any runoff) due to changes in future climate states. As for the increased precipitation,
43 the magnitude of the probable maximum precipitation/probable maximum flood (PMP/PMF) is
44 not likely to change significantly in a wetter climate, based on the conservatism associated with
45 the estimation of the PMP and the proper computation of the PMF. If the FEP, future erosion,
46 cannot be excluded, it should be included in the analyses described in Table 2-1.

1 A drop in sea level could change the erosion rates of certain coastal areas due to an increase in
2 topographic gradients. Sea level variations have been documented by various organizations
3 and there is a general consensus that sea levels have dropped to 110 to 120 m below current
4 sea level during the glacial periods of the current Quaternary ice age (NOAA, 2008; Gornitz,
5 2007; IPCC, 2001). If a proposed disposal facility is associated with a coastal area, the licensee
6 should perform an erosion analysis assuming a sea level drop of 120 meters (m). Other drop
7 magnitudes may be evaluated if a licensee provides adequate technical basis for the magnitude
8 of the sea level drop. The licensee needs to analyze subsequent changes in erosional force
9 due to sea level drop and evaluate the estimated effects on a future disposal cell.

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

21
22 Even on a qualitative level, the probability of future tsunami hazards for a particular location
23 would be too difficult to estimate over the performance period. The level of effort required to
24 evaluate future tsunami hazards is likely to be excessive and technical analyses is not
25 warranted considering the short duration that a potential disposal site would be flooded by a
26 tsunami.

27 Flood Plains and Wetlands

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

33
34
35 Flooding can directly influence the performance of the disposal system or trigger another
36 process, such as erosion, that can impact the performance of the disposal system. Higher
37 topographic areas generally have fewer floodplains and wetlands; the effects of erosion usually
38 become problematic before flooding. On the other hand, depositional areas and relatively flat
39 areas would have a potential of becoming flood plains and wetlands.

40
41 Knowledge of the past surface hydrology in the potential disposal area can be used to
42 strengthen the qualitative FEP assessment. For example, the surface hydrology of southern
43 Louisiana is quite diverse. The Mississippi River and other rivers have changed river channel
44 beds numerous times and 100-year floodplains would change in concert with river course
45 evolution. Disposal sites for significant quantities of long-lived waste should not be located in
46 the vicinity of these channels.

47
48 Features and processes identified in studies of the past natural history of the area often provide
49 an indication of what processes will likely be present in the future. If, for example, an area has

1 been frequently flooded during and immediately after past glacial periods to create intermittent
2 glacial lakes (e.g., Lake Missoula, Lake Lewis, and Lake Bonneville), the probability is high that
3 similar processes and events will occur during the performance period.
4

5 Geomorphologic evidence may provide useful data on large paleofloods. The evidence can
6 include slack-water deposits, scour lines, high-water marks, and undisturbed areas (Stedinger
7 and Cohen, 1986). The advantage of paleoflood data is that it can improve a probabilistic flood
8 hazard assessment and extend short or non-existent flood records to include the last 1,000 to
9 10,000 years (Klinger and England, 2013). Paleoflood data can improve the estimates of the
10 magnitude and frequency of large floods. Licensees should develop an assessment of the
11 potential for future flooding and for local floodplain and wetland formation in the future.
12

13 In addition, paleoflood data may provide evidence of large, dynamic floods, similar to the
14 “outburst” floods that occur when the water of dammed glacial lakes are suddenly unobstructed.
15 Such massive, violent floods could destroy a disposal site located close to the surface and
16 thereby fail to meet the site stability performance objective (i.e., 10 CFR 61.44). Potential sites
17 located in areas affected by previous glacial processes and/or subjected to previous massive
18 flooding would require additional analysis and careful evaluation. Although the site and
19 immediate area would not be habitable for humans and a potential receptor, the contaminated
20 material may remain in a relatively concentrated form while being deposited downstream near
21 more habitable locations where receptors could exist. Potential disposal sites located in areas
22 subject to previous massive flooding may require deeper disposal and additional man-made
23 barriers (e.g., engineered surface covers) to mitigate the destructive force of large floods.
24

25 **10 CFR Part 61.50(a)(2)(iii):** *The disposal site must provide sufficient depth to the water*
26 *table that groundwater intrusion, perennial or otherwise, into the waste will not*
27 *occur. The Commission will consider an exception to this requirement to allow disposal*
28 *below the water table if it can be conclusively shown that disposal site characteristics will*
29 *result in molecular diffusion being the predominant means of radionuclide movement*
30 *and the rate of movement will result in the performance objectives of Subpart C of this*
31 *part being met. In no case will waste disposal be permitted in the zone of fluctuation of*
32 *the water table.*
33

34 A potential site located in an area with a relatively large number of wells and data on
35 groundwater fluctuations should be sufficient for a licensee to perform FEP screening
36 associated with depth to water table. An area without sufficient data on the local water table
37 and associated groundwater fluctuations may need additional site characterization. Features of
38 interest for a licensee are current water table elevation and soil types, including sediment layers,
39 with the potential for creating a perched water zone. A licensee should identify the
40 hydrogeologic units of the layers below the disposal site. For example, a caliche layer or dense
41 clay may cause temporary perched zones that may only exist on a seasonal basis. It should be
42 sufficient for a licensee to identify such features in combination with meteorological data,
43 topography of the disposal system, and processes of the local hydrogeology in their analysis of
44 current water table behavior.
45

46 The requirement at 10 CFR 61.50(a)(2)(iii) is closely related to the requirement at
47 10 CFR 61.50(a)(2)(i) (i.e., poor drainage and flooding). Future water table elevation is partially
48 a function of the current landscape and potential changes to the landscape in the future. As
49 with the requirement in 10 CFR 61.50(a)(2)(i), topography, hydrogeology, erosion rate, and

1 precipitation rates are determining factors for water table elevation. With updated studies on
2 long-term trends, past natural history, and PMP/PMF, it should be possible for a licensee to
3 develop an assessment to bound potential water table changes. Water tables in topographic
4 highs or steep areas may have a greater degree of seasonal variability, but generally would be
5 expected to have a smaller potential to significantly change during the long term than would a
6 relatively flat, depositional area that is susceptible to drought and flooding. Depending on the
7 hydrogeology of the region, a low-lying or depositional area today can experience a rising water
8 table or even become a flood plain in a future wetter climate.

9
10 A number of tools and codes are available to licensees to support analyses and assessments of
11 groundwater discharge that can be used to assist in making a determination regarding long-term
12 water table fluctuations. Knowledge of the paleoclimatology, paleopedology, and past hydrology
13 of the potential disposal area can support the assessment of this requirement. For example,
14 arid regions with wetter conditions in the past may have had higher water tables, but never
15 close enough to the surface to have posed a threat to a potential future disposal site. However,
16 evidence of the past has revealed that features such as wetlands and lakes had previously
17 existed in currently arid areas. Death Valley is a good example: generally dry and waterless,
18 this valley had been flooded in the past (Lake Manly) and was persistent enough to support a
19 native population. Death Valley is currently dry because of the extremely low rate of
20 precipitation at and near the area. However, a geomorphologist, or a qualified specialist, would
21 recognize that its topography is ideal for lake formation, if more water were to become available
22 (as evidence from its geological past has shown). Other areas may receive a high rate of
23 rainfall, but the topography and geology will not allow for lake formation in the future.

24
25 In general, the climatic history during the Quaternary period has been of a cyclic nature
26 consisting of glacial and interglacial stages. Features and other evidence of the past natural
27 history can assist in reconstructing the full cyclic climatic history including precipitation rate and
28 temperature ranges. Potential disposal sites further to the south may never have experienced
29 glacial coverage in recent geologic history. Knowledge and evaluation of the full cyclic
30 extremes, and updated studies of topographic trends (e.g., surface uplift, tectonic subsidence,
31 erosion vulnerability, etc.), can help a licensee in developing an assessment that could
32 potentially bound long-term water table fluctuations, even if these fluctuations may have been
33 extreme. Potential disposal sites further to the north may have been previously covered by
34 glaciers that cause disruptive surface geologic processes so that the requirement
35 10 CFR Part 61.50(a)(4)(iv) becomes the primary focus.

36
37 **10 CFR Part 61.50(a)(2)(iv):** *The hydrogeologic unit used for disposal shall not*
38 *discharge groundwater to the surface within the disposal site.*

39
40 The criterion in 10 CFR 61.50(a)(2)(iv) is closely related to the criterion in 10 CFR 61.50(a)(2)(i)
41 and 10 CFR 61.50(a)(2)(iii). Groundwater discharge areas are partially a function of the current
42 landscape and any potential changes to the landscape in the future. As with the requirement in
43 10 CFR 61.50(a)(2)(i), topography, hydrogeology, erosion rate, and precipitation rates are
44 determining factors if water will discharge in a certain area. Any time a water table rises higher
45 than the ground surface, groundwater will discharge to the surface. The assessment done for
46 10 CFR 61.50(a)(2)(iii) should assist in determining if the hydrogeologic units used for disposal
47 are able to discharge groundwater to the surface within the disposal site under current or
48 projected future conditions. A licensee should compare the approximate rise and fall of the
49 water table assessed in 10 CFR 61.50(a)(2)(iii) to the changes in topography.

1
2 Different combinations of trends should be considered by licensees: net mass change
3 (deposition/erosion) and net change on water table (rising/falling). For example, it is possible
4 that areas with relatively stable long-term water table levels may also experience relatively high
5 erosion rates; the net effect is a water table advancing to the ground surface. It is unlikely,
6 however, that such sites would fulfill the requirement of 10 CFR 61.50(a)(4)(iv) which states that
7 areas with significant surface geologic processes must be avoided. Site characterization should
8 provide sufficient data to a licensee on geology, hydrogeology, topography, paleoclimates, and
9 features and processes to qualitatively assess the plausibility of groundwater discharge
10 occurring sometime in the future. Evidence supporting the existence of past groundwater
11 discharge areas, such as calcite deposits or diatomite, vastly increases the chances that the
12 disposal area will have groundwater discharge occurring during the analyses timeframes.

13
14 **10 CFR Part 61.50(a)(4)(iii):** *Areas must be avoided where tectonic processes such as*
15 *faulting, folding, seismic activity, or volcanism may occur with such frequency and extent*
16 *to significantly affect the ability of the disposal site to meet the performance objectives of*
17 *Subpart C of this part, or may preclude defensible modeling and prediction of long-term*
18 *impacts.*

19
20 Tectonic processes, such as faulting, folding, seismic activity, and volcanism, are processes
21 that might lead to short disruptive events, but unlike the processes associated with other
22 disposal site suitability requirements, these processes are linked with plate tectonics that
23 proceed at very slow rates. The assessment and evaluation carried out for the compliance and
24 protective assurance periods to approximate the frequency and extent of faulting, folding,
25 seismic activity, and volcanism in a particular area, as discussed in NUREG-1200, should not
26 lead to significantly different results when applied to the performance period. These are long-
27 term processes and unlike the processes related to the previously discussed site suitability
28 requirements, water is not directly involved. Tectonic processes are large-scale processes and
29 the frequency and extent of seismic and volcanic activity will not vary much when extrapolated
30 to the performance period. The licensee should conduct a thorough assessment of
31 10 CFR 61.50(a)(4)(iii) based on the guidance in NUREG-1200 and NUREG-1199.

32
33 **10 CFR Part 61.50(a)(4)(iv):** *Areas must be avoided where surface geologic processes*
34 *such as mass wasting, erosion, slumping, landsliding, or weathering occur with such*
35 *frequency and extent to significantly affect the ability of the disposal site to meet the*
36 *performance objectives of Subpart C of this part, or may preclude defensible modeling*
37 *and prediction of long-term impacts.*

38
39 FEPs that could cause changes in the frequency and extent of the surface geologic processes
40 are climate, topography, geology, soil type, type of flora, water chemistry, and the matrix in
41 which the water flows. Short-term, large-scale topographic change normally does not occur
42 unless associated with a disruptive event. The frequency and extent of water (i.e., precipitation
43 rate) has the greatest potential for driving rates of mass wasting, erosion, slumping, landsliding,
44 or weathering. NUREG-1623 provides guidance on surface geologic processes. FEPs that
45 could cause unsuitable rates of erosion include increased rainfall and/or an increased gradient
46 (and therefore, an increase in the erosional power of any runoff). As for the increased
47 precipitation, the magnitude of the PMP/PMF is not likely to change significantly in a wetter
48 climate, based on the conservatism associated with the estimation of the PMP.

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

15
16 The massive ice covers of the glacial periods were a source of extensive, large-scale surface
17 geologic processes. Figure B-9 shows the approximate area covered by glaciers during the last
18 three glacial periods of the current Quaternary ice age (i.e., the Wisconsin, Illinoian, and Pre-
19 Illinoian glacial periods). Glaciers can cause very disruptive surface geologic processes, and
20 potential sites located in areas affected by previous glacial processes could require additional
21 analysis and careful evaluation.

22
23 Evidence of the past natural history of the area, or from an appropriate natural analog, should
24 provide support to licensees for excluding, or retaining, the FEPs associated with the surface
25 geologic processes. Pedogenic processes, biotic activities, and bioturbation are all processes
26 that may impede or accelerate surface geologic processes. Thick root systems from certain
27 plants are known to greatly reduce the erosional force; however, it is difficult to rely on the
28 continuous presence of a specific plant that might be needed for longer timespans. Any number
29 of factors could influence flora such as drought, fire, disease, fungi, and insects.

30 2.5.3.1.2.2 Probability

31
32 Licensees use screening criteria, based on the probability of occurrence and/or consequences
33 to the performance of the disposal system, to screen out FEPs that are unlikely to occur or that
34 have relatively minor consequences. Three methods that a licensee may consider that handle
35 probability depending on the extent of quantification of the FEPs concerned include (EC,
36 2009a):

- 37
38 • *Quantitative methods*, where all FEPs are represented numerically and event probability
39 is an explicit part of the performance assessment calculation, such as those methods
40 employed in the probabilistic models used for the Yucca Mountain and Waste Isolation
41 Pilot Plant projects. For example, a performance assessment required by
42 10 CFR Part 63 should not include consideration of very unlikely FEPs (i.e., FEPs that
43 are estimated to have < 1 chance in 10,000 within 10,000 years of occurring). As a
44 result, FEPs with probabilities lower than 10^{-8} /yr should be screened out during the
45 scenario development process. The probability classification in its entirety would include
46 the following and could be used in conjunction with the qualitative approach as points of
47 reference:

- 1 ○ Implausible: Very Unlikely ($<10^{-8}/\text{yr}$)
- 2 ○ Plausible: Unlikely or Less Likely ($<10^{-5}/\text{yr}$ and $>10^{-8}/\text{yr}$)
- 3 ○ Plausible: Reasonably Foreseeable ($>10^{-5}/\text{yr}$ or >1 chance in 100,000 per year
- 4 or about a 1 in 10 chance of occurring over a 10,000 year period)
- 5 • *Qualitative methods*, where the probability or likelihood of occurrence of FEPs is
- 6 described qualitatively or semi-quantitatively, and probability values are not an explicit
- 7 part of the numerical modeling. However, a qualitative description of probability could
- 8 still be used (e.g., unlikely vs. very unlikely). Qualified specialists would need to
- 9 determine the level of probability, as well as the terminology to be used to describe that
- 10 probability. For example, experts on paleofloods may determine that a site's physical
- 11 environment and topography preclude major flooding. The low probability from this
- 12 qualitative determination could then be labeled as either "very unlikely" or "implausible"
- 13 or some other term depending on the terminology agreed upon. The level of effort for
- 14 this method is appropriate for LLW disposal sites and is recommended for the analysis
- 15 of FEPs.
- 16 • *Non-consideration of probability*, especially where few or no relevant data are available
- 17 and there are large uncertainties associated with describing the scenario. With this
- 18 method, FEPs are included as a result of lack of information.

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

23 24 *Uncertainty Associated with Probability*

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

33
34 When there is sufficient and reliable information available, an analyst can have confidence in
35 probability estimates and the understanding of uncertainty in the probability estimates. If the
36 sampled population on which the probability is based is small or the quality of the data is poor,
37 or if the estimates are based on assumptions, then the uncertainty associated with probability
38 can be high. As previously discussed, long-term analyses or estimates may be more difficult to
39 quantify due to an increasing scarcity of reliable data. The probability of occurrence for an
40 earthquake above a certain magnitude over a 100-yr. period would be uncertain however the
41 confidence in the probability estimate may be relatively high when compared to the uncertainty
42 in the probability of tundra-like conditions occurring at a particular location many thousands of
43 years in the future. When using probability to screen FEPs, the uncertainty in the probability
44 must be taken into account.

1 2.5.3.1.2.3 Consequence
2

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

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

15
16 A performance assessment model will commonly have inter- and intra-dependent components
17 or submodels. For this reason, the initial development process should err on the side of
18 including FEPs of unclear significance. Once the model is developed and the connection and
19 communication of submodels have been established, then the significance determination
20 process can more reliably eliminate FEPs.
21

22 The inclusion or exclusion of a FEP in a performance assessment model depends on whether it
23 has a measureable, observable, or significant effect on disposal system performance. Since
24 FEPs are not measurable or observable in the far future, expert judgment will constitute a key
25 element of the screening process. Experts or specialists would need to determine the
26 magnitude of the consequence, as well as the terminology to be used to qualitatively describe
27 that impact (e.g., significant, major, substantial). For example, if it is plausible that the
28 consequence of a FEP can be expected to change dose results that are relatively close to the
29 performance objective, then the impact of the feature or phenomenon in question is significant.
30 In addition, if the output results change by orders of magnitude depending on the absence or
31 presence of a feature, or the occurrence or absence of a phenomenon, then the impact of the
32 feature or phenomenon is significant. Previous performance assessments may provide insights
33 to consequence, or additional modeling or sensitivity analyses could assist in determining the
34 impact. Depending on the complexity of the system, this process may need to be iterative.
35

36 Since subsystem-level effects on system-level performance may be masked by certain designs
37 and/or combinations of input parameter values, the quality of the FEP analysis relies on the
38 qualifications and judgment of the analysts. In addition, the licensee using consequence-based
39 FEP screening should consider the interrelationships of the FEPs with one another, and the

1 effect different combination of FEPs may have on the consequence (e.g., if an engineered
2 surface barrier cover is performing as planned, the performance of other engineered features
3 may be masked for a specific period of time).

4 Uncertainty Associated with Consequence

5
6 When there is sufficient and reliable information available, an analyst can have confidence in
7 consequence estimates and the uncertainty may be low. If there is limited information, the
8 quality of the data is poor, or if the estimates are based on assumptions, then the uncertainty
9 associated with consequence may be high. In addition, if qualified specialists have difficulty
10 determining masking effects, the uncertainty associated with consequence estimates can be
11 high. As previously discussed, the interrelationships of the FEPs with one another, and the
12 effect different combinations of FEPs may have on the consequence should be considered to
13 the extent possible. For example, variable temperature and chemical composition of
14 groundwater may affect the rate of radionuclide transport. Distribution coefficient (K_d) values for
15 radionuclides may also change due to the changing environments. However, these different
16 FEPs (inherent groundwater variability vs. temporal variability in the environment) may affect the
17 K_d values for individual radionuclides in opposite ways. In other words, it may be challenging to
18 determine the consequence of a single FEP when many FEPs are uncertain as to their
19 influence on the results. High uncertainty in the consequence of a FEP should result in the FEP
20 being included, unless even with the uncertainty the FEP can be shown to not likely to be
21 significant or the timing of occurrence will be delayed outside of the regulatory analysis
22 timeframes.

23 2.5.3.1.2.4 Screening Techniques

24
25 Although there may be different ways to organize, evaluate, and present the FEPs, most
26 methods have certain similarities and the lists of retained FEPs obtained by different methods
27 should be similar. Techniques are not mutually exclusive and licensees may use several tools
28 in combination. The following section outlines one systematic screening technique, but there
29 may be other valid techniques that a licensee may use.

30
31 Systematic FEPs screening by licensees will involve the use of professional judgment.
32 Screening criteria matrices categorize phenomena into various elements according to the
33 magnitude of the probability and the consequence (Hommel, 2012; NEA, 1992). For example,
34 Table 2-2 illustrates the approach of using a combination of probability and consequence of a
35 FEP, in conjunction with the uncertainty associated with that FEP, to retain or screen out the
36 FEP (IAEA, 2004). Screening criteria matrices require specialists and experts to select the
37 FEPs they estimate to be important and include in the assessment. Screening criteria matrices
38 are one method that can provide transparency. Table 2-2 presents an example matrix that
39 licensees can use to perform FEP screening for a LLW disposal facility performance
40 assessment. Factors used for initial screening purposes include (1) probability of the FEP, (2)
41 consequence of the FEP, and (3) the uncertainties associated with the probability and
42 consequence.

43
44 Depending on the probability, a phenomenon or feature can be placed either below or above a
45 screening value as seen in column 2 of Table 2-2. FEPs can be screened in or out if a
46 qualitative screening limit is selected and applied. For example, analysts may decide that FEPs
47 with “very unlikely” probabilities should be screened out while FEPs with an “unlikely” probability
48 should be included in the scenario development. The third column divides the uncertainty

1 associated with the probability into high and low uncertainty. Consequence is handled in a
 2 similar manner as probability, which can be seen in columns 4 and 5 in Table 2-2. Analysts can
 3 assign a qualitative consequence screening limit in addition to an uncertainty estimate
 4 associated with the consequence. After being evaluated, a FEP will have assigned
 5 designations for the probability, consequence, and their uncertainties. Based on these
 6 designations, the qualified specialists will screen FEPs in or out, as shown in the far right-hand
 7 column.

8
 9 **Table 2-2 Example of Screening Criteria Based on Qualitative Probabilities,**
 10 **Consequences, and Uncertainty Associated with a FEP**

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

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

11 Whether a FEP is screened in or out is apparent in most of the 16 cases in Table 2-2. For
 12 example, in case 1, a FEP is clearly screened out since both probability and consequence are
 13 below a screening limit and their associated uncertainties are small. Conversely, FEPs in cases
 14 13-16 are retained for scenario development despite the various degrees of associated
 15 uncertainty since probability and consequence are both above their screening limits. Some of
 16 the cases are not as straightforward and are worth discussing in more detail below.

17
 18 For cases 2 through 4, cases 2 and 3 have probability and consequence below predetermined,
 19 qualitative screening limits. For case 2, the uncertainty associated with consequence is low and
 20 for case 3, the uncertainty associated with probability is low, giving the analyst sufficient
 21 confidence to exclude the FEP from further consideration. For case 4, there is less confidence
 22 since both probability and consequence have a high uncertainty associated with them and
 23 although probability and consequence are below screening limits, the uncertainties associated

1 with both probability and consequence would lead the analyst to keep the FEP for scenario
2 development during the compliance period.

3
4 Cases 5 through 8 all have consequences above the screening limits indicating potential
5 inclusion of FEPs for further consideration; however, the uncertainty associated with the
6 probability is important to determining their final inclusion or retention. If there is low uncertainty
7 associated with a probability lower than a screening limit, there is confidence that despite the
8 higher impact or consequence, the probability of its occurrence is sufficiently unlikely so that the
9 FEP could be screened out (cases 5 and 7). Whereas, if there is high uncertainty associated
10 with the small probability, as in Cases 6 and 8, the FEP should be screened into the analysis.

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

19
20 Increased uncertainties associated with the phenomena and features of the protective
21 assurance period compared to the compliance period would be reflected in the potentially
22 increasing number of FEPs and the uncertainties associated with probabilities and
23 consequences of the FEPs. As a result, a larger number of FEPs may be retained based on
24 this increasing uncertainty. However, FEPs from the protective assurance period with
25 probabilities and consequences that are both below their respective screening limits should be
26 screened out and not included in any scenarios for the protective assurance period if they have
27 not already been included in the compliance period analysis. For case 4, both probability and
28 consequence are associated with high uncertainty, although both are below screening limits.
29 For the compliance period, the uncertainties associated with both probability and consequence
30 would lead the analyst to keep the FEP for scenario development. If the FEP continues to be
31 present or occur during the protective assurance period, this FEP would be part of the scenario
32 development for this period. However, if a FEP is new to the protective assurance period and
33 not a feature or phenomenon of the compliance period, the FEP would not be part of the
34 scenario development for assessment for that period (see far right-hand column in case 4).

35
36 A licensee may extend compliance period calculations into the future without modification,
37 provided that the calculations are complete with respect to including key FEPs relevant to the
38 protective assurance period or excluding FEPs only relevant to the compliance period.
39 However, since the protective assurance period is considerably longer than the compliance
40 period, FEPs that have been excluded from further consideration in the compliance period may
41 not be able to be screened out from further consideration for the protective assurance period
42 analyses. Potentially significant FEPs may need to be considered during scenario development
43 if disruptive processes are expected to start occurring during the protective assurance
44 timeframe or if the cumulative impact from repetitive events over the longer timeframes is not
45 included and the repetition of those processes and events could lead to significant impacts.

1 **2.5.3.2 Top-Down Approach**
2

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

13 **2.5.3.2.1 Safety Assessment and Safety Functions**
14

15 Safety assessments are a systematic analysis of the ability of the site and design to provide the
16 safety functions and meet technical requirements. A safety function is defined qualitatively as a
17 role through which a component of the disposal system contributes to safety. Safety functions
18 are the diverse capabilities and components of the barriers found within a disposal system that
19 are used to reduce the potential for the release of radioactive material and to ensure that any
20 releases are within acceptable limits. The safety functions may differ as the time period
21 changes. For example, the capabilities of a surface cover component may be relied upon to
22 achieve short-term safety objectives for a LLW disposal site while the long-term capabilities of
23 the wasteform itself may be relied upon for the long-term safety functions. Analogous to the use
24 of a fault tree analysis for nuclear reactor safety (NEA, 1992), knowing when a safety function is
25 expected to be available and when it can be relied upon will affect scenario development.
26

27 A safety assessment and the findings of the safety assessment are essential components of the
28 collection of arguments and evidence in support of disposal system safety. Other components
29 supporting the safety of a radioactive waste disposal facility should include:
30

- 31 • A description of the waste and the rationale for the chosen waste management strategy;
- 32 • Descriptions of the disposal concept, the disposal facility, the disposal site and its safety
33 functions;
- 34 • Description of the management system applying to the different phases of facility
35 development; and
- 36 • Any other information that support continued development, operation, and closure of the
37 facility.
38

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

2.5.3.2.2 *Safety Functions and Scenario Development*

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

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

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

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

2.5.4 Constructing Scenarios

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

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

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

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

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

2.5.4.1 Central Scenarios and Alternative Scenarios

A licensee should use scenarios to describe the scenario uncertainty associated with the system. The central scenario is the expected evolution of the system; the alternative scenarios are less likely but cannot be eliminated by the licensee. Scenarios allow for the licensee to use

1 a mixture of quantitative analyses and qualitative judgments. The selected scenarios should
2 together provide an appropriately comprehensive technical description of the estimated
3 performance of the disposal system.

4
5 Central scenarios are usually based on extrapolation of existing conditions into the future and
6 incorporation of changes expected to occur in the future. The central scenario is considered to
7 be the scenario best supported by available information and is usually considered to be a
8 benchmark scenario against which the impact of alternative scenarios can be compared.

9 The central scenario represents how the licensee expects the system to evolve assuming the
10 proper functioning of the design with anticipated degradation. All of the significant features and
11 processes that exist at a site should be captured by the central scenario. The central scenario
12 is generally devoid of consideration of major events that change the future evolution of the site
13 and the performance of the disposal system since most licensees will be selecting a potential
14 disposal site where such events are not expected. It is acceptable for a licensee to treat
15 anticipated future evolutions of the disposal system in one numerical model by varying
16 parameter ranges. However, because the disposal system may evolve differently under
17 alternative scenarios, it may be difficult to represent the different plausible FEPs all in one
18 simulation model and additional models may have to be constructed.

19
20 Licensees should also develop plausible, alternative scenarios to investigate the impact of
21 scenarios that are not expected but cannot be excluded. A licensee is not required to evaluate
22 implausible alternative scenarios. However, there may be some utility for a licensee to evaluate
23 sequences of events and conditions independent of probabilities, in order to illustrate the
24 significance of individual barriers and barrier functions. In other words, the robustness of the
25 disposal system can be examined. These alternative scenarios may represent less likely, but
26 still plausible, modes of disposal site evolution (e.g., processes that impede the effectiveness of
27 a feature important to waste isolation) as well as scenarios representing extreme natural events
28 (e.g., earthquakes, volcanic activity, or glaciers) but that are still within the range of realistic
29 possibilities within the analyses timeframe. Generally, a limited number of external FEPs will be
30 of concern.

31
32 Various graphical and tabular techniques have been used to assist in scenario development
33 (NEA, 1992; IAEA, 2004; NRC, 1995c; SKB, 2008). These techniques may be useful for a
34 licensee to consider. These techniques include:

- 35
- 36 • Event trees, logic diagrams, and related approaches that analyze alternative
37 combinations of events and/or of resulting system states
 - 38 • Fault and/or dependency diagrams that set out in a hierarchical fashion the conditions
39 and/or processes leading to, or contributing to, an end point of interest
 - 40 • Influence diagrams that map the dependencies or interactions between various
41 processes, often indicating the importance of the interaction
 - 42 • Interaction matrices that force a comprehensive questioning of the dependencies
43 between selected key features or processes
 - 44 • Audit tables that force a consideration of the representation of each FEP within the
45 available models and system representation, and evaluation of bias due to omission or
46 simplified representation

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

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

2.6 Conceptual Model Development

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

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

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

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

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

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

10
11 The “safety assessment comparison approach” relies on the expert judgment and experience of
12 the analyst carrying out the assessment. The first step is to identify the key release, transport,
13 and exposure media by reviewing the relevant FEPs associated with each scenario. The
14 mechanisms by which the associated release, transport, and exposure may occur are
15 considered for each scenario.

16
17 Two strategies can be used based on information derived from each scenario:

- 18
19 • The deductive strategy reviews how release events might occur and considers the
20 possible transport and exposure mechanisms and the associated impacts;
- 21 • The inductive strategy analyzes the impacts, considers the exposure and transport
22 mechanisms that might have caused the impacts, and the associated release
23 mechanisms.

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

40
41 The “influence diagram approach” for developing a conceptual model also allows the interaction
42 between FEPs to be identified in a logical and systematic way. Advantages and disadvantages
43 are similar to the interaction matrix approach, although the influence diagram generally contains
44 more detail than the interaction matrix. FEPs are represented by boxes and interactions
45 between FEPs are illustrated by arrows showing the influence direction. The number of arrows

1 between two FEPs will be equal to the number of influences between them. Only direct
2 influences should be represented in an influence diagram.

3 **2.6.1 Alternative Conceptual Models**

4
5 Licensees should adequately describe and document conceptual model uncertainties. The
6 performance assessment documentation should provide the assumptions, limitations, and
7 uncertainties of the models. Multiple representations of the system may be consistent with the
8 available data. In general, licensees should select the conceptual models that best represent
9 available data and associated uncertainty. However, when data are sparse, multiple conceptual
10 models may represent the available data. In this case, licensees should select the conceptual
11 model that provides the most conservative result, or additional data could be collected to reduce
12 uncertainty and determine which alternative conceptual model provides the most realistic
13 representation. All conceptual models do not need to be abstracted and evaluated, but all
14 models that are reasonably consistent with available information should be considered.
15 Reviewers should perform an independent evaluation of model uncertainty and consider
16 whether more than one conceptual model should be evaluated, especially for complex sites.

17 **2.7 Numerical Model Development and Assessment**

18
19 The numerical model development and implementation process typically consists of
20 representing the conceptual models and their associated processes in mathematical models,
21 and using modeling software to develop numerical simulations of the mathematical models.
22

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

26 **2.7.1 Numerical Models⁴**

27
28 In general, licensees will rely on numerical or computational models to estimate the future
29 performance of a disposal site. However, the implementation of mathematical models in
30 computer codes may not be necessary in all cases depending upon the complexity of the
31 analysis. Additionally, the analyses are intended to be iterative and the level of detail and effort
32 involved in a particular iteration may vary depending on the phase of facility development and
33 the level of knowledge about the disposal site. For instance, during siting of the facility, simple
34 models may initially be used to screen candidate sites, whereas, more sophisticated models
35 may be needed during licensing of sites with unique characteristics such as complex site
36 engineering or natural features. Although specific computer codes may be discussed or
37 referenced in this guidance, the NRC does not endorse the use of any particular code or
38 modeling software package for analyzing the performance of a LLW disposal site.
39

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

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

2.7.1.1 Selection and Implementation

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

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

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

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

Because long-term behavior of the disposal system is of particular interest for numerical models that estimate the performance of LLW disposal facilities, licensees should provide comparisons between theory and experimental results, field observations, and other supporting information that may involve interpretation and extrapolation. In cases where more than one mathematical

1 formulation may be appropriate, licensees should document why a particular formulation is
2 preferred to the discarded approaches and, importantly, the limitations of the selected approach.
3 Licensees may also wish to consult Appendix I of Safety Guide No. GS-G-3.4 for information
4 about controlling the numerical models for waste disposal facilities (IAEA, 2008).
5

6 Reviewers should evaluate the conceptual model(s) and the numerical models to ensure
7 compatibility with the site conceptual model including the source-term, transport pathways, and
8 receptor scenario. For example, numerical models designed for the onsite receptor scenario
9 may not be appropriate for assessment of an offsite receptor scenario. Reviewers should also
10 ensure that the assumptions in the numerical modeling are consistent with the site conceptual
11 model and that any deviations will not significantly affect the ability of the numerical model to
12 represent the conceptual model. Reviewers should investigate the sensitivity of numerical
13 model calculations to variations in input ranges to ensure that the model is numerically stable
14 over the range of input parameters for expected site conditions. The range of input parameters
15 may be different for alternative scenarios compared to the central scenario.
16

17 Licensees may select available modeling software, commercially-available or otherwise, or
18 develop codes or modeling platforms specifically for site-specific purposes. The modeling
19 software may be proprietary codes, modified codes, and/or codes specifically developed for
20 implementation of the chosen mathematical models. Modified codes and codes specifically
21 developed for a site-specific application are referred to generically in this guidance as “user-
22 developed” codes. The use of proprietary codes usually has the advantage that the codes have
23 been previously developed and checked. Proprietary codes may have a history of application to
24 a range of different analogous problems. In contrast, user-developed codes need to be
25 developed and checked by licensees. However, they do have the advantage of being tailored to
26 the needs of the specific problem to be addressed. In all cases, it is necessary for a licensee to
27 consider the process of software design based on a given mathematical specification (IAEA,
28 2004). Licensees should ensure that the software used for the numerical models is in
29 conformance with the active standards of the IEEE Standards for software development, quality
30 assurance, testing, verification, and validation (e.g., IEEE Standard 730-2002, IEEE Standard
31 for Software Quality Assurance Plans). Reviewers should be familiar with NRC’s Software
32 QA/QC guidance (i.e., NUREG/BR-0167, NUREG-0865) to ensure the licensee’s QA/QC
33 procedures for selection and development of numerical models are comparable. It is
34 recommended that proprietary codes are peer reviewed by the appropriate technical community
35 prior to use in a licensing decision; however peer review is not required. The pertinent regulator
36 may need to perform this function. Further guidance on software QA/QC is provided in the
37 following section.

38 **2.7.1.2 Quality Assurance**

39

40 Licensees may develop computer codes or may use available codes (e.g., previously developed
41 or commercially available) to simulate the performance of the disposal site using the site
42 conceptual model. An essential element of modeling software development and/or usage is
43 quality assurance (QA). Quality assurance associated with the field of code development is
44 reasonably mature; this section of the document does not attempt to provide detailed guidance

1 on software development. However, the main elements of software QA are discussed here. As
2 part of QA for software development⁵, a licensee should develop documentation of:

- 3
- 4 (1) Software requirements and intended use
- 5 (2) Software design and development; the software development process (if used), should
6 be planned, controlled, and documented.
- 7 (3) Software design verification; software verification should be planned, documented, and
8 performed.
- 9 (4) Software installation and testing
- 10 (5) Configuration control
- 11 (6) Software problems and their resolution
- 12 (7) Software validation; planning should include validation methods and validation criteria.
- 13

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

18
19 The following bullets provide the information a licensee should provide and a reviewer should
20 evaluate with respect to numerical model development.

- 21
- 22 • Valid data should be used in the numerical model. The data used in the analysis should
23 be traceable⁶ to their sources through all calculations and data reductions.
- 24 • The data should have been obtained or qualified under an acceptable QA program (e.g.,
25 an NRC-approved QA program developed to meet the requirements of 10 CFR Part 50,
26 Appendix B).
- 27 • The numerical model should be demonstrated to adequately represent the processes or
28 systems for which it is intended.
- 29 • The software should perform intended functions, provide correct solutions, and not
30 cause adverse unintended results.

31 **2.7.2 Model Abstraction and Model Simplification**

32 Model Abstraction

33 A licensee will need to abstract the conceptual models they develop in order to translate the
34 concepts into mathematical terms. Model abstraction is the process of abstracting a conceptual
35 model representing a dynamic site in the physical world into a mathematical model governed by
36 equations which is implemented within a numerical model. It is the process of determining the
37 level of detail that should be preserved in the overall performance assessment model (or
38 intruder assessment model). Figure 2-5 provides the types of abstraction that may occur in the
39

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

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

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

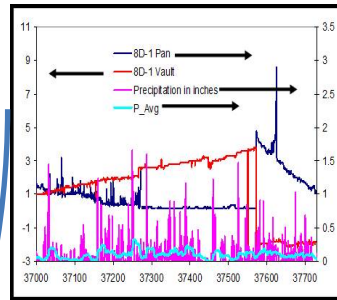
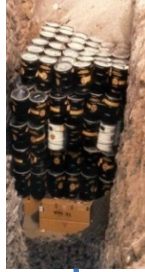
12
13 Several factors can affect the complexity of the models that a licensee may use. Some level of
14 simplification is generally required in order to translate the concepts of a conceptual model into
15 mathematical terms. This simplification can take several forms, such as:

- 16
17 • The simplification of the geometry or structure—for example, considering a transport
18 medium to be homogeneous and isotropic
- 19 • The omission of processes and interactions—for example, neglecting kinetic terms in
20 chemical reactions
- 21 • A reduction in spatial or temporal resolution

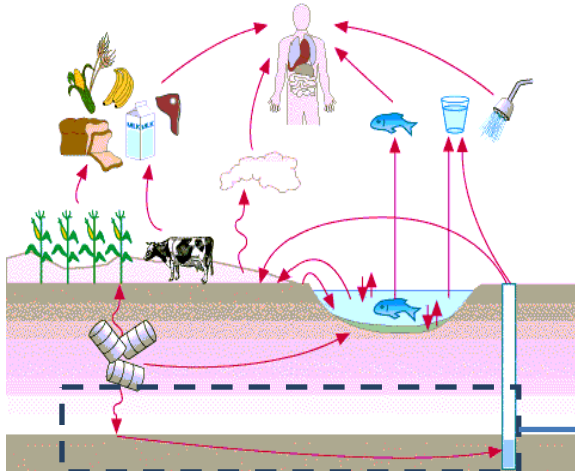
22 23 Model Simplification

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

38
39 It is important that a licensee should clearly document both model abstractions and model
40 simplifications. A licensee may need to perform abstraction of the real world system into a
41 mathematical model using an iterative process. It is useful for a licensee to factor in limitations
42 of the computational platform during conceptual model development. However, it is not
43 appropriate to limit the assessment to the capabilities of existing computational platforms. In
44 some cases, a licensee may need to develop a new computational model in order to
45 appropriately assess the problem.



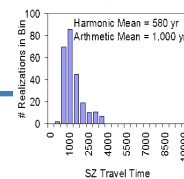
Site characterization data and other information



Performance assessment conceptual model development

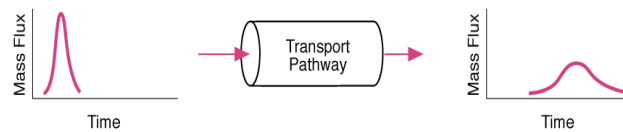
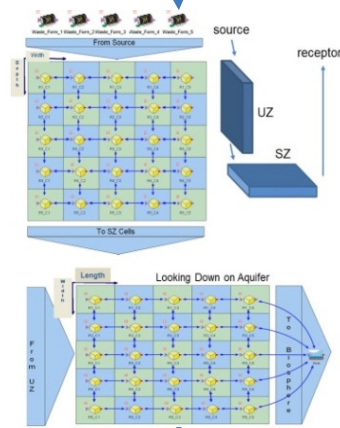
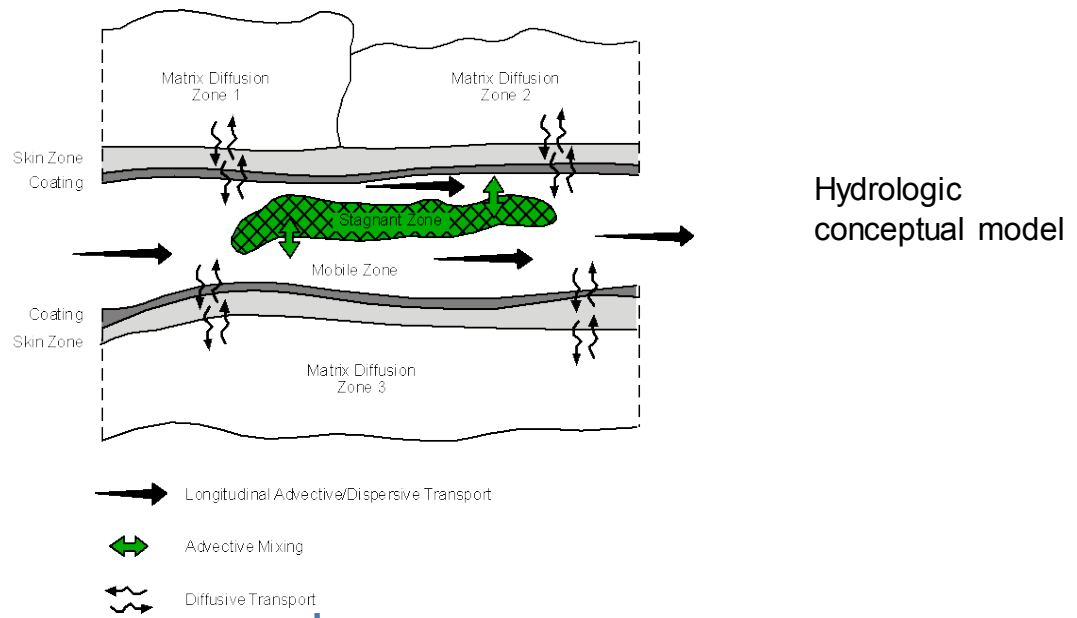
Hydrologic conceptual model development (see next figure)

Estimated system performance



Abstracted hydrologic model

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



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

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

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

7 **2.7.3 Model Integration**

8
9 The objective of the review of integration is to determine if the site and design description, data,
10 parameter uncertainty, models, and model uncertainty have been appropriately integrated in the
11 assessment. The reviewer should ensure that representations of the disposal system design
12 and natural system features have been adequately integrated into the technical analyses.
13 Assumptions, data, and models should be consistent throughout the technical analyses.
14 Inconsistencies should be explained in the documentation or be corrected. Boundary and initial
15 conditions should be consistent between different submodels in the performance assessment.
16 Information that is passed between submodels should be verified to be of the appropriate
17 temporal and spatial scale. If different models are used, information passed between models
18 should be assessed to determine if unit conversions were made. Graphical representations can
19 be useful to communicate integration in the technical analyses. Influence diagrams can be
20 useful to document concisely the connections among submodels in the performance
21 assessment.

22 **2.7.4 Analysis and Evaluation of Results**

23
24 Probabilistic approaches to performance assessment are preferred in most cases because they
25 readily permit the propagation and assessment of the impact of uncertainty on the model
26 results. However, use of a deterministic model to demonstrate compliance with performance
27 objectives may be acceptable. In general, if deterministic modeling is used, it should be
28 reasonably conservative, such that a subject matter expert, with minimal interaction with those
29 who performed the assessment, could conclude that the analysis is conservative. Independent
30 reviewers should evaluate the modeling in sufficient detail to be confident that the analysis is
31 conservative.

32
33 For probabilistic analysis, the appropriate metric to use for comparison with the annual dose
34 limits is the peak of the mean result. The peak of the mean is calculated by estimating the
35 mean dose result over all probabilistic realizations, then taking the peak value of the mean
36 curve. In some cases the mean curve may represent a high percentile of the projected output.
37 Licensees may propose more conservative metrics; however, the NRC staff believes that the
38 peak of the mean is protective.

39
40 If a probabilistic approach is used for the performance assessment, the reviewer will need to
41 determine whether there is significant "risk dilution" affecting the calculation results. Risk
42 dilution results when overly broad parameter distributions are selected primarily for processes
43 that affect the timing of impacts. Although large uncertainty ranges may seem to be
44 "conservative," overly broad uncertainty ranges can artificially depress the peak of the mean
45 dose result. For example, selection of an overly broad range for the K_d for neptunium-237 in the
46 saturated zone may result in the estimated time of arrival of the contaminant at a receptor

1 location being artificially spread over the period of performance, thereby "diluting" the risk at any
2 one point in time.

3
4 For modeled processes and input parameters that are highly uncertain and cannot clearly be
5 established as conservative, sensitivity analyses are necessary to establish the relative
6 importance of these processes and parameters to the performance assessment dose
7 calculations. NUREG-1757 (NRC, 2006; Volume 2, Appendix I, Section 1.7) and NUREG-1573
8 (NRC, 2000a; Section 3.3.2) summarize different methods for sensitivity and uncertainty
9 analyses. Sensitivity analyses may identify the need for additional site characterization to
10 adequately support the technical analyses.

11
12 Key parameters for further evaluation in a *sensitivity analysis* may be selected with a variety of
13 different approaches, and the appropriateness of the approaches depends on the problem. It is
14 anticipated that the sensitivity analysis and the performance assessment overall may be an
15 iterative process. The initial approach evaluated may not be the final approach selected.
16 Regardless of the process, the reviewer should keep in mind that the purpose of the sensitivity
17 analysis is to evaluate uncertainty and variability in the assessment. One of the simplest
18 methods uses a top-down approach in which the risk reduction of each component (e.g.,
19 infiltration, unsaturated zone, wasteform, engineered barriers, saturated zone, biosphere
20 characteristics) of the performance assessment model is identified by starting with a hazard and
21 calculating how each component reduces the risk from the hazard. Subsequently, for the most
22 important components, the licensee performs a quantitative or qualitative evaluation of the
23 parameters to identify those that are most likely to influence the output from the component.
24 Complications arise because an individual component's importance in the system can be
25 relative to the performance of other components. For example, the hydraulic conductivity of a
26 drainage layer may not appear to be risk-significant as long as a cover is assumed to
27 significantly limit water flow, but the drainage layer may be very important to performance if the
28 cover is degraded. Section 7.4.1.2 discusses methods to avoid such problems. Developing an
29 understanding of the importance of parameters and models in a performance assessment is a
30 time-consuming process that is best accomplished by exploring a variety of approaches.

31
32 If the licensee has performed a deterministic performance assessment, then the reviewer
33 should examine the sensitivity analyses provided. The reviewer should evaluate the licensee's
34 basis for selecting the parameters and combinations of parameters used in the sensitivity
35 analysis. The ranges in the parameters selected should be consistent with the variability and
36 uncertainty in the parameters, and the selected ranges should provide the reviewer with
37 confidence that the effects of the uncertainty on performance are bounded. The reviewer
38 should examine the technical basis used to support the variability and uncertainty. Appropriate
39 combinations of parameters should be used to capture the interdependence of key parameters
40 and the consequences associated with changes in combinations of key parameters. The
41 reviewer should consider combinations of parameter values that are likely to occur as a result of
42 common causes. For example, an aggressive chemical environment could increase both the
43 corrosion rate of waste containers and the rate of leaching of radionuclides from a wasteform. If
44 a licensee were to perform analysis of the increased corrosion rate independent from analysis of
45 increased leaching rate of radionuclides from the wasteform, the true risk significance of an
46 aggressive chemical environment may not be identified.

47
48 Different approaches to performance assessment calculations (e.g., deterministic, probabilistic)
49 have advantages and disadvantages with regard to uncertainty and sensitivity analysis. The

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

3.0 PERFORMANCE ASSESSMENT

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

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

3.1 Performance Assessment Approach

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

- (1) A description of the site and engineered system,
- (2) An understanding of FEPs that might affect the disposal system,
- (3) A description of processes controlling the movement of radionuclides from the LLW disposal units to the environment,
- (4) A computation of doses to members of the public, and
- (9) An evaluation of uncertainties.

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

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

Disposal system behavior is characterized by the disposal facility design, the characteristics of the waste, geologic and environmental characteristics of the disposal site, and processes and events that influence the aforementioned features. The performance assessment identifies the specific characteristics of the disposal site (e.g., hydrology, meteorology, geochemistry, biology,

1 geomorphology); degradation, deterioration, or alteration processes of the engineered barriers
2 (including the wasteform and container); and interactions between the site characteristics and
3 engineered barriers that might affect the performance of the disposal facility. The performance
4 assessment examines the effects of these processes and interactions on the ability of the
5 disposal facility to limit waste releases to the environment that could cause annual dose to a
6 member of the public.

7
8 The performance assessment should be performed iteratively and is meant to be a tool for both
9 the licensee and the regulator to use in assessing whether the disposal facility meets the
10 10 CFR Part 61.41 performance objective. During the design and licensing of a disposal site,
11 assumptions may be made, based on expected waste volumes and streams, of the possible
12 final inventory of a site or a specific disposal unit within a site. As operations occur, these
13 assumptions should be updated periodically with actual waste volumes and any revised
14 information on future waste to be received (see Section 10.0). The results of the performance
15 assessment can then be used to evaluate whether reasonable assurance still remains that the
16 disposal unit or site will continue to meet the performance objectives. If the performance
17 assessment shows that meeting the performance objective is uncertain or unlikely, then the
18 licensee should consider taking the following actions: additional data collection and modeling
19 could be performed, the facility could be modified, or future waste volumes or specific
20 radionuclide quantities or concentrations could be reduced (i.e., through setting “allowable”
21 limits, see Section 9.0). The decisions on what actions to take should involve the site operator,
22 the appropriate regulator(s), and other stakeholders.

23 3.1.1 Example of a Performance Assessment Approach

24
25 An example of an acceptable approach for conducting a performance assessment and
26 demonstrating that the requirements in 10 CFR 61.41 would be met is outlined below. The
27 approach is divided into 12 steps, as shown on Figure 3-1:

- 28
- 29 • Step 1: Conduct initial data evaluation of information needed to describe the LLW
30 disposal system environment — Formulate the context of the assessment. Describe the
31 disposal system and the environment of the site.
 - 32 • Step 2: Describe plausible evolutions of the disposal site — Identify and consider
33 credible factors or processes that could contribute to affecting a radionuclide release,
34 including changes to the disposal site over time from natural processes and events, and
35 construct reasonably foreseeable scenarios to evaluate in Step 5 for compliance with the
36 performance objective and less likely, but plausible scenarios for evaluating defense-in-
37 depth in Step 7.
 - 38 • Step 3: Describe initial conceptual models and parameter values or distributions —
39 Develop site-specific conceptual models based on important disposal site features and
40 processes.
 - 41 • Step 4: Formulate mathematical models and select codes — Formulate mathematical
42 representations of the conceptual models, using appropriate documentation and quality
43 assurance/quality control (QA/QC). Numerical model development incorporates the
44 mathematical representations and produces computational models with which to run
45 simulations.

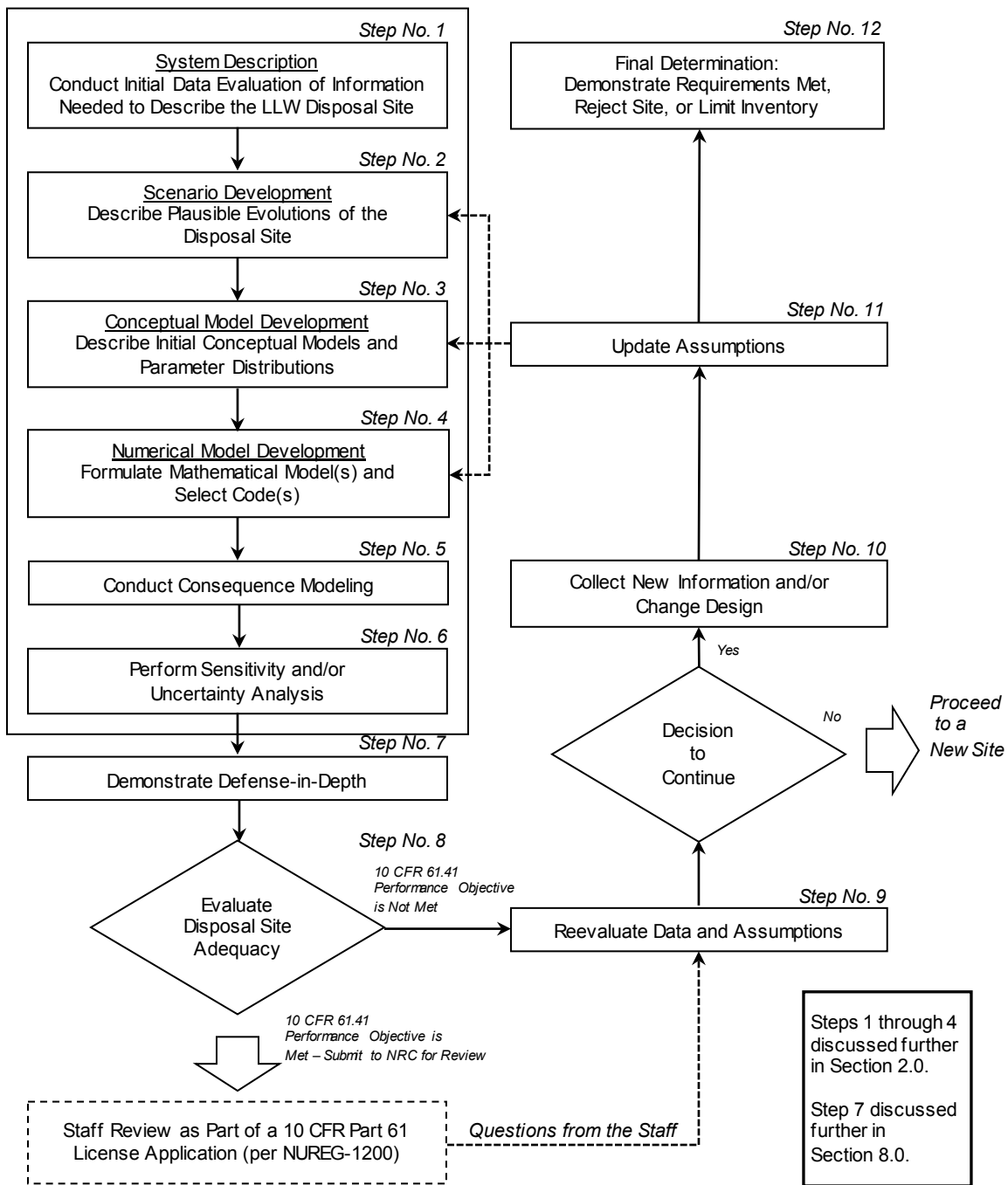
- 1 • Step 5: Conduct consequence modeling — Estimate performance (e.g., potential dose
2 to members of the public). See Sections 3.4 and 4.3.1 for further discussion. Much of
3 the receptor scenario approach used in Section 4.3.1 can be applied in the performance
4 assessment.
- 5 • Step 6: Perform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

26
27 Additional guidance on an example performance assessment approach can be found in
28 NUREG-1573, Section 3.1 (NRC, 2000a). Sections 2.0 of this document provide additional
29 guidance on Steps 1 through 4 above.

30 **3.1.2 Role of the Performance Assessment**

31
32 To obtain a license to receive, possess, and dispose of LLW, disposal facility operators should
33 use the performance assessment to demonstrate, with reasonable assurance, that the
34 10 CFR 61.41 performance objective for protection of the general public will be met. Further,
35 the results of a performance assessment can be used to support defense-in-depth analyses
36 required in 10 CFR 61.13(f). Licensees may use the results of the performance assessment to
37 quantify barrier capabilities and their associated uncertainties to understand their contribution to
38 safety and defense-in-depth. Section 8.0 of this document provides additional guidance on
39 using the results of the performance assessment to demonstrate defense-in-depth protections
40 are included.

41



1
2
3
4

Figure 3-1 Example of a Performance Assessment Process

1 During construction, operation, and post-closure periods of the LLW disposal facility, the
2 performance assessment can continue to have an important role in demonstrating that the
3 performance objectives continue to be met. The performance assessment is a projection into
4 the future to provide the bases for the decision to proceed.
5

6 The other steps in the operation and closure process can be used to confirm (or refute) the
7 basis for the initial decision. For example, 10 CFR 61.53 requires a licensee to perform
8 environmental monitoring during the construction, operation, and post-operational periods.
9 Similarly, 10 CFR 61.28 requires that a final revision to site closure plans should contain any
10 additional geologic, hydrologic, or other disposal data obtained during the operational period
11 pertinent to the long-term containment of waste, and the results of tests, experiments, or
12 analyses pertaining to the long-term containment of waste, including revised analyses for
13 10 CFR 61.13 using the details of the final closure plan and waste inventory. Site closure may
14 be authorized only if the final site closure plan provides reasonable assurance of the long-term
15 safety of the facility.
16

17 The performance assessment can be used to address these requirements by updating the
18 performance assessment model developed for the initial license application with the new
19 information from these monitoring programs. These new site data might validate or refute the
20 key parameters or model assumptions used in the initial performance assessment. Section 9.5
21 provides information on mitigation, which might be identified as being necessary to continue
22 meeting the 10 CFR Part 61 performance objectives as a result of conducting an updated
23 performance assessment upon site closure. Section 10.0 of this document discusses the role of
24 performance assessment in performance confirmation. Additional discussion of general
25 technical elements as they relate to performance assessment appears in Sections 2.0 of this
26 document.
27

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

36 **3.2 Source Term**

37

38 The objective of source term modeling is to calculate radionuclide releases from the disposal
39 units over time and space. Licensees can use the calculated release rates as input for transport
40 models (see Section 3.3) that estimate offsite releases for the facility. The source term includes
41 the inventory, physical and chemical characteristics, and other properties of the waste used to
42 estimate release rates. The inventory of waste is the physical amount of material and quantity
43 of radioactivity contained in the waste. Releases generally occur by advective or diffusive
44 mechanisms, although direct release mechanisms may be possible (e.g., biointrusion, erosion).
45 Release rates are also a function of the conditions of the environment immediately surrounding
46 the waste (i.e., the near-field environment). The near-field environment may have hydrological
47 and chemical conditions that differ significantly from the natural system in which the waste

1 disposal facility is located. Additional releases to the aqueous phase and, for certain
2 radionuclides (e.g., carbon-14, hydrogen-3, radon-222), to the gaseous phase, can also occur.
3 Licensees may simulate many intermediate processes to estimate release rates. Release rates
4 can be affected by the performance of engineered barriers (e.g., waste containers) and the
5 wasteforms, the chemical properties of the disposal system, and the interaction of the disposal
6 system with the natural environment in which it is located. Licensees should identify these
7 processes using the guidance in Section 2.5 regarding the analysis of FEPs. Some disposal
8 facilities will require detailed consideration of these processes and conditions, whereas
9 simplified analyses may be justified for other sites and disposal facilities. Licensees should
10 carefully consider the source term models for those disposal sites where significant credit is
11 taken for some aspect of the source-term modeling (e.g., low *solubility limits*), attributes are
12 relied upon for defense-in-depth protections, or higher long-term hazard exists, and for which
13 there is limited model support. Facilities for which a simpler, less complex, analysis may be
14 acceptable include those where a licensee can show that a simple analysis is clearly
15 conservative or where a licensee provides a simple model that is well-supported by multiple
16 lines of evidence, including field tests demonstrating that the model estimates are accurately
17 representative or bounded by field data.

18

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

26

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

32

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

43

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

1 (NRC, 2007a). Section 3.3.7 of NUREG-1573 and Section 4.3.5 of NUREG-1854 present
2 guidance on radionuclide transport, biosphere characteristics, and dose modeling.
3

4 Section 2.7.2 of this guidance document describes general elements of technical analyses that
5 are applicable to the review of a source term abstraction for performance assessment. Since
6 this guidance supplements existing guidance, licensees and reviewers may also consult
7 NUREG-1573, Section 3.3.5, for further guidance on source term modeling. Also, NUREG-
8 1854, Section 4.3.3, may assist reviewers in considerations for acceptable source term
9 modeling that may apply to review of a performance assessment for a LLW disposal facility.
10

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

18 **3.2.1 Inventory**

19

20 The inventory representation provides the *radionuclide inventory* for which release rates are
21 estimated with source term calculations. Sections 3.3.5.1, 3.3.5.2, and 3.3.5.7 of NUREG-1573
22 (NRC, 2000a) and Sections 3.1 and 4.3.3.1.1 of NUREG-1854 (NRC, 2007a), as applicable to
23 LLW disposal facilities, provide guidance on recommended approaches for developing and
24 reviewing waste inventory to support performance assessment modeling.
25

26 The radiological inventory to be disposed of is a key input parameter to the performance
27 assessment. In addition, the physical and chemical characteristics of the waste can determine
28 release rates. Physical characteristics can affect the stability of the waste and the stability of
29 the disposal facility (see Section 5.0). Chemical characteristics can affect the retention of
30 radionuclides within the disposal facility. Chelating or complexing agents can significantly
31 increase the mobility and effective solubility of the radionuclides in the disposal environment.
32

33 A licensee should develop an inventory description that provides the total activity (by
34 radionuclide), concentrations, and physical and chemical forms of the waste to be disposed of,
35 including spatial configurations. The inventory description should include the radiological
36 inventory at the time of disposal, as well as the projection of inventory over the time period of
37 interest to account for decay and ingrowth.
38

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

1 estimate the inventory, the licensee should describe where the waste has been generated and
2 what isotopes are used or created in the associated processes.

3
4 Different waste streams may have significantly different characteristics. However, it may be
5 useful for a licensee to compare their projected inventory to the inventory of other LLW disposal
6 facilities. The similarity or dissimilarity of the radiological inventories can help a reviewer to
7 identify isotopes that may dictate the need for a more detailed review of the inventory estimates.
8 In some cases, specific isotopes may be reported as less than a particular value because the
9 isotope was below the lower detection limit of the characterization technique. It is acceptable to
10 assign inventory based on the lower detection limit for initial screening. However, if the initial
11 screening identifies that specific isotope inventory as significant, then additional characterization
12 (either direct or indirect) may be necessary to determine the actual inventory with greater
13 confidence. It is generally not acceptable to assume a value of zero for the inventory of
14 radionuclides that are less than the lower detection limit unless there is adequate justification
15 that the radionuclide is not present in the waste.

16 **3.2.2 Chemical Environment**

17
18 Estimation of the chemistry of the environment within the disposal units may be needed for use
19 in source term models. The chemical environment may have impacts on and be affected by the
20 lifetime of engineered barriers and waste containers, releases of radionuclides from the
21 wasteforms, and mobility within the disposal units. The chemical environment in the disposal
22 site is likely to be dynamic unless the site has been engineered to provide a more stable
23 chemical environment. The chemistry of the disposal units would likely have an impact on
24 solubility limits or retardation of radionuclides that are common parameters in modeling release
25 rates from the source term and through the environment. Geochemical considerations may
26 include solid composition, pH, buffering capacity, reduction-oxidation potential, partitioning
27 processes, and the presence of colloidal particles and ligands.

28
29 In general, licensees are encouraged to collect site-specific information to justify parameters
30 that would be expected to significantly enhance or retard the release and migration of
31 radionuclides or that are relied upon for defense-in-depth protections. Licensees may use
32 sensitivity analyses to identify the importance of geochemical parameters on the resulting dose
33 either to identify whether site-specific data should be obtained for significant parameters, or to
34 determine whether the range of values used is sufficiently conservative for parameters that do
35 not have a significant effect. Section 2.2.2 presents guidance on the treatment of uncertainty. It
36 may also be appropriate to use other means to justify parameters, such as values from available
37 literature, appropriate geochemical process modeling (e.g., MINTEQA2 (EPA, 1991); EQ3/6
38 (Daveler and Wolery, 1992; Wolery, 1992a and 1992b; Wolery and Daveler, 1992); PHREEQC
39 (USGS, 1999); Geochemists Workbench® (Bethke and Yeakel, 2009a–d)),¹ or expert judgment
40 and expert elicitation (see Section 2.2.3.1). Licensees should judiciously select the proper
41 literature values for significant parameters and transparently describe the similarities and
42 discrepancies between the site conditions to which they are proposed to represent and the
43 conditions from which the literature values were derived. A reviewer should determine if the

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

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

3
4 The abstraction for the chemical environment should consider the uncertainty and variability in
5 developing geochemical parameters. Variability in the chemical environment of a site can occur
6 spatially and temporally. Spatial variability may arise from heterogeneities in wasteforms and
7 other materials introduced to the disposal units (e.g., backfill materials, cementitious materials).
8 Temporal variability may arise from the degradation of engineered barriers, waste containers,
9 and wasteforms as well as the evolution of the disposal site environment to future conditions.
10 Licensees should consider the impacts of the evolution of the natural environment on the
11 chemical environment as a result of degradation of the engineered barriers and natural
12 processes such as climate change. A licensee should document their treatment of spatial and
13 temporal variability in the chemical environment model. The documentation should provide the
14 technical basis for the representation. For example, if a constant environment was used in the
15 performance assessment modeling, the licensee should demonstrate why the constant
16 environment was representative or conservative with respect to the projected future chemical
17 environment.

18
19 Section 3.3.5.6 of NUREG-1573 presents guidance on considerations and issues associated
20 with developing models for the chemical environment of the disposal units (NRC, 2000a).
21 Section 4.3.3.1.4 of NUREG-1854 provides guidance on reviewing a chemical environment
22 representation (NRC, 2007a). Additional considerations, as they apply to a specific facility, may
23 also be found in Section 4.2.1.3.3 of NUREG-1804, Revision 2, "Yucca Mountain Review Plan,"
24 issued July 2003 (NRC, 2003c).

25 **3.2.3 Waste Container**

26
27 Waste container modeling describes the waste containers and estimates their longevity for use
28 in source term models. In the past, licensees have generally not taken much credit for the
29 performance of waste containers in their technical analyses; however, they are not prohibited
30 from doing so. The waste container modeling should consider degradation processes
31 (e.g., corrosion, mechanical degradation) for the various waste containers and should be
32 consistent with the evolution of the chemical environment (see Section 3.2.2). The performance
33 of the waste containers may also affect the degradation of wasteforms and is important for
34 estimating radionuclide release in the source term models. Section 3.3.5.4 of NUREG-1573
35 includes guidance on evaluating the performance of waste containers (NRC, 2000a). In
36 addition, waste containers are a component of an engineered barrier system. Therefore,
37 reviewers may want to consult applicable guidance on reviewing engineered barriers in
38 Section 3.3.4 of NUREG-1573 and Section 4.3.2 of NUREG-1854 (NRC, 2007a). Sections
39 4.2.1.3.1 and 4.2.1.3.2 of NUREG-1804 present additional considerations for the performance
40 of engineered barriers with respect to the waste containers (NRC, 2003c).

41
42 Metallic containers will undergo corrosion over time. Most metallic containers used in LLW
43 disposal are carbon steel; however, other types of steel may be more commonly used in the
44 future. If a licensee takes credit for waste containers in the performance assessment, they
45 should provide a degradation analysis to justify the performance of the containers. The
46 degradation analysis should look at the degradation processes (e.g., general corrosion,
47 stress-corrosion cracking, localized corrosion, galvanic corrosion, radiolytic effects) and the
48 disposal environment to estimate future performance. The degradation analysis should

1 consider the initial condition of the containers (e.g., corrosion prior to disposal). In humid
2 disposal environments, failure of carbon steel containers due to general corrosion is expected to
3 be relatively quick, such that little credit for performance (e.g., delay in releases) is commonly
4 taken in the analyses. In arid environments, licensees may take more credit for container
5 performance, if supported by the degradation analysis which will examine the materials,
6 environmental conditions, and degradation mechanisms. Licensees should support engineering
7 analysis of container performance with measurements in relevant environmental conditions. In
8 addition, licensees should provide real-world engineering analogs. The engineering analogs
9 should be for similar exposure conditions and should not include maintenance, since the
10 disposal containers will not be maintained after disposal. Section 2.2.3 provides additional
11 information with respect to developing model support, including the use of analogs.

12
13 Analysis of container failure will need to consider variability, as leakage from containers may
14 occur as soon as the first perforation occurs. The state of corrosion that defines “failure” will be
15 different for different release mechanisms. A perforated waste container may still provide a
16 significant barrier to mass transfer processes for some time. However, in general, when the
17 corroded area exceeds approximately 10 percent, the container can be considered to be failed
18 from an advective release standpoint due to shedding of water from intact areas to failed areas.

19
20 Containers made of other (i.e., non-metallic) materials will experience degradation unique to the
21 material type. Reviewers should evaluate proposed container lifetimes for different materials on
22 a case-by-case basis. In general, the licensee’s associated degradation analysis will need to
23 provide the following:

- 24 • an assessment of the relevant degradation mechanisms
- 25 • a description of the environmental conditions including variability and uncertainty
- 26 • analysis of the expected performance
- 27 • an assessment of potential unexpected performance and the likelihood of the
28 unexpected performance
- 29 • data from laboratory, field, and/or analog observations that support the expected
30 performance
- 31

32 **3.2.4 Wasteform and Waste Type**

33
34 The wasteform modeling representation is used to describe wasteform performance, including
35 variability. Wasteform performance is used in source term models. The modeling should
36 consider degradation processes for the various wasteforms to estimate their performance
37 consistent with the evolution of the chemical environment in the disposal units over the time
38 period of interest (see Section 3.2.2). The performance of the wasteform is important for
39 estimating radionuclide release in the source term models.

40
41 The branch technical position on wasteform provides recommendations and guidance on
42 acceptable methods to demonstrate that waste stability requirements have been met (NRC,
43 1991b). Appendix A to the technical position on wasteform provides methods to ensure the
44 suitability of cement-stabilized wasteforms. *Geochemical Aspects of Radioactive Waste*
45 *Disposal* describes some wasteforms and their properties (Brookins, 1984). Every wasteform is

1 different and can have different characteristics. However, the main elements in Appendix A of
2 the wastefrom BTP apply to wastefroms other than cement-based wastefroms.

3
4 These elements include:

- 5 • qualification testing,
- 6 • quality of sample preparation,
- 7 • consideration of variability,
- 8 • waste characterization, and
- 9 • short- and long-term specimens including *surveillance* specimens.

10
11 It is important for licensees and reviewers to note that waste stability from a structural
12 standpoint does not necessarily translate into acceptable performance for waste leaching.
13 Depending on the concentration of radioisotopes in the waste, the fractional release rate of an
14 individual isotope necessary to demonstrate that the performance objectives would be met may
15 be lower than that necessary to demonstrate waste stability.

16
17 Radionuclide release from wastefroms can be very complex, with a number of processes
18 controlling the mobility and concentrations of radionuclides. Processes such as complexation
19 reactions, acid-base reactions, oxidation-reduction reactions, dissolution and precipitation
20 reactions, sorption and ion-exchange reactions, biodegradation of organic matter, and
21 radioactive decay and ingrowth can impact waste release rates. A variety of test methods and
22 modeling approaches have been developed to characterize the release of contaminants
23 (NRC, 2010). The following guidance is developed on the basis of information in
24 NUREG/CR-7025. In this report, Ebert identified a number of key lessons with respect to waste
25 release that included:

- 26 • Test results can be misinterpreted if testing artifacts are not taken into account
27 (e.g., interval for solution replacement, flow rates, failure to reach steady state, modeling
28 of inappropriate processes).
- 29 • A single test method may not identify mechanisms controlling release.
- 30 • It is necessary to identify which processes control release under the conditions of
31 interest (i.e., the test conditions should be representative of expected conditions,
32 including variability).
- 33 • Laboratory test results need to be translated to long-term material behavior
34 (i.e., appropriate scaling, which may include multiple variables, is necessary).
- 35
- 36

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

41
42 Test methods can be categorized as static, semi-static (where part or all of the solution is
43 exchanged during the test), or dynamic (where solution flows continuously). Different test
44 methods can yield different results; licensees should carefully interpret the test results to avoid
45 misinterpretation or mischaracterization of the release mechanism. For example, the American
46 Nuclear Society 16.1 (ANS, 2008) leaching method is a solution-exchange test to characterize
47 diffusion-controlled release. The test results are sensitive to the sampling intervals that are

1 used to measure the extent of component releases. While the test is useful for screening, it is
2 not recommended for modeling long-term waste degradation. Methods such as American
3 Society for Testing and Materials (ASTM) C1308-08 (ASTM, 2009), which uses constant
4 exchange intervals, may be more useful in determining whether waste release is diffusion
5 controlled or affinity controlled. Column tests are useful in simulating the infiltration of water
6 through the subsurface to waste and the dissolution of contacted materials. The measured
7 dissolution rate in column tests is a function of the flow rate of the solution and the reactive
8 surface area that is contacted. Different column tests may need to be performed for different
9 materials and to account for the variable emplacement of those materials. A primary challenge
10 is the scaling of the laboratory results to the field which may have much different flow rates and
11 reactive surface areas than used in the laboratory. Additionally, the flow rates and reactive
12 surface areas in the wastefrom can vary over time. When some materials leach, the reactive
13 surface area may increase or decrease from the leaching process. Release rates from some
14 materials may be much higher under conditions of wet-dry cycling as compared to non-dynamic
15 conditions. The value of column tests (or tests such as field-scale lysimeters) is to confirm that
16 the appropriate performance models are used to quantify the processes that control
17 radionuclide release, especially when calibrated to the system of interest.

18
19 Because of the complexity of waste release modeling, the NRC staff recommends that
20 licensees complete a blind validation of the numerical model results to test the predictive
21 capabilities of the numerical model. This is done by establishing a condition for which waste
22 release measurements have not been completed and performing numerical simulations of the
23 waste release that would be expected to occur under those conditions. This is followed by
24 experimental or field measurements of the actual waste release that is compared to the
25 numerical modeling. Licensees should establish criteria before the blind comparison to define
26 acceptable agreement between the numerical modeling results and the experimental
27 measurements.

28
29 Additional information can be found Section 3.3.5.4 of NUREG-1573, which includes guidance
30 on information to characterize wastefroms and types (NRC, 2000a). Section 4.3.3.1.2 of
31 NUREG-1854 presents guidance on wastefroms and their time-dependent degradation
32 (NRC, 2007a).

33 **3.2.5 Aqueous Release**

34
35 The models for aqueous releases estimate the rate of radionuclides released from the disposal
36 units in water contacting the wastefroms. The four general types of aqueous radionuclide
37 releases are: (1) rinse release, (2) diffusional release, (3) dissolutional release, and
38 (4) partitioning release. Rinse release refers to washing of radionuclides from the surface of a
39 wastefrom by infiltrating groundwater. Diffusional releases occur when radionuclide movement
40 through a porous wastefrom (e.g., a cement-stabilized wastefrom) is limited by diffusion.
41 Diffusion can occur in any media in the presence of a concentration gradient. Radionuclide
42 releases resulting from corrosion of an activated metal or dissolution of glass wastefroms are
43 examples of dissolutional release. Partitioning release results when radionuclide release is
44 described by a characteristic partitioning parameter (e.g., sorption coefficient) that distributes
45 the activity between phases in the system (e.g., between the solid wastefrom and liquid water
46 phases).

47

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

10
11 Licensees should consider comparison of laboratory test results, such as leaching experiments,
12 with numerical modeling results. If field data are available, they provide information that can be
13 used for model support. For example, observed concentrations of radionuclides in leachate
14 collection systems can be compared to modeled release rates. Section 4.3.3.2 of NUREG-1854
15 (NRC, 2007a) and Section 4.3.1.2.4 of NUREG-1804 (NRC, 2003c) provide additional guidance
16 on potential considerations for development or review of aqueous release models.

17 **3.2.6 Gaseous Release**

18
19 Models for gaseous release estimate the rate of radionuclides released in the gas phase from
20 the disposal units to the atmosphere above the disposal facility. A gaseous release model may
21 also need to consider the generation of nonradioactive gases and their impact on the
22 capabilities of the disposal facility to contain and isolate the radioactive waste. Examples of
23 important radionuclides that should be considered and evaluated by licensees for gaseous
24 release include C-14, Kr-85, Rn-222, H-3, and I-129. Gaseous releases are dependent on both
25 generation of the gas and transport through fluids within the disposal units to the atmosphere.
26 Discrete features such as fractures or a gap between materials can have a significant impact on
27 gaseous release rates.

28
29 In Section 3.3.5.7.2 of NUREG-1573, the NRC staff recommends a screening approach to
30 determine if gaseous releases from the disposal facility might contribute significantly to dose
31 (NRC, 2000a). Licensees may apply this approach to determine whether more realistic release
32 rates would be needed. More realistic release rates may be developed by licensees using
33 approaches described in NUREG-1573 or approaches listed in the discussions below. Realistic
34 release rate modeling should consider the specific processes affecting generation and transport
35 of gaseous radionuclides or empirical models of gaseous release rates. In general, licensees
36 are encouraged to collect site-specific information to justify parameters that would be expected
37 to significantly enhance or retard the release and migration of gaseous radionuclides should
38 they significantly affect doses to a member of the public.

39 **3.2.6.1 Gas Generation**

40
41 Gases generated in a LLW disposal facility may result directly from disposal of certain waste
42 streams (e.g., Kr-85) or from various processes external or internal to the disposal site.
43 Processes generating gases, many of which are discussed in Section 3.3.5.7.1 of
44 NUREG-1573, may include: (1) corrosion of metals in waste and its packaging, (2) microbial
45 degradation of organic waste components, (3) radiolysis of waste, its packaging, or the
46 surrounding backfill material, (4) volatilization of certain wastes (e.g., iodine-129), and (5) decay
47 of radionuclides with primordial origin (e.g., uranium-238 or thorium-232) to gaseous progeny

1 (e.g., radon-222). Rodwell et al. (2003) summarizes considerations for many of these
2 processes as they relate to deep geological radioactive waste repositories. This information
3 may be relevant for licensees to consider in a performance assessment for LLW disposal
4 facilities. The evaluation of gas generation by a licensee should account for the nature of the
5 waste, the radionuclides it contains, the waste packaging materials, and the chemical
6 characteristics of the environment within the disposal units (e.g., saturation, groundwater
7 composition, pH, Eh, and backfill materials) (NEA/OECD, 2001).

8 **3.2.6.2 Radon Emanation**

9
10 Conservation of linear momentum in the alpha-decay process of high-specific-activity
11 radionuclides can result in transport of radionuclides (i.e., alpha recoil). Typically this process is
12 not significant for the release and transport of radionuclides from a LLW disposal facility.
13 However, alpha recoil can be significant for certain gaseous radionuclides (e.g., radon)
14 associated with some long-lived waste streams. Alpha recoil can result in newly created radon
15 atoms moving away from their original location. Some end up in the particles (media) where
16 they were created, some end up in adjacent particles, and some end up in the pore space. The
17 radon emanation coefficient is a dimensionless parameter that expresses the fraction of radon
18 released to the pores (compared to the total volume). Guidance on the radon emanation
19 coefficient is provided here due to the potential significance of this unique process and radon's
20 presence in the decay chain for long-lived waste streams associated with uranium.

21
22 The radon emanation coefficient is strongly influenced by the liquid saturation of the medium
23 (Nazaroff et al., 1988). As liquid saturations vary temporally and spatially, it is expected that
24 radon emanation coefficients will also exhibit temporal and spatial variability. The values for
25 radon emanation coefficients depend on the liquid saturation (or moisture content), the media,
26 and the radon isotope.

27
28 Yu et al. (1993) provides a limited compilation of radon emanation coefficients. The compilation
29 shows the large variability that can be observed; soil values ranged from 0.02 to 0.70. Nielsen
30 and Rogers (1988) provides a probability plot of emanation coefficients for 56 soils. The values
31 range from approximately 0.08 to 0.44 (with a mean of 0.22), consistent with the observed
32 variability in the data of Yu et al. Regulatory Guide 3.64, "Calculation of Radon Flux Attenuation
33 by Earthen Uranium Mill Tailings Covers" (NRC, 1989a) for calculation of radon fluxes from mill
34 tailings covers recommends a default value of 0.35 for design, which would correspond to a
35 98th percentile value from the Nielson and Rogers data *for soil*. The challenge is that the data
36 represent both intra- and inter-site variability. If site-specific measurements are not available,
37 licensees should select conservative values from the compilations (as was done in Regulatory
38 Guide 3.64) because the inter-site variability should not be credited in a site-specific analysis.
39 For long-term performance assessment calculations, it is important to recognize that the values
40 selected for the analysis are representative of values anticipated for the evolution of site
41 conditions. Average parameter values (spatial and temporal) can be used if it can be
42 demonstrated that the variability is not important to estimating radon fluxes. However, because
43 of the nonlinear processes governing radon release and transport, the variability in emanation
44 coefficients and other parameters may drive the long-term fluxes. For example, at a moderately
45 humid site, radon fluxes may be dominated by the periodic dry conditions.

46

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.

1 Licensees that undertake more detailed modeling of gas phase transport from disposal units
2 may need to consider some or all of the aforementioned processes and models in the models
3 for gaseous release, depending on the site conditions. For instance, molecular diffusion may be
4 the only mechanism to consider for equimolar gases under isobaric, isothermal conditions that
5 diffuse in pores much larger than the mean free path of the gas molecules, whereas a Dusty
6 Gas Model approach might be necessary for gas migration through low-permeability materials
7 under a pressure gradient to account for coupled advective-diffusive processes. Important
8 parameters of these models (e.g., permeability, saturation, pore space dimensions) should be
9 well-supported and, to the extent practicable, based on conditions that are representative of the
10 site environment. In other words, site observations supporting parameter values should be
11 made under expected conditions for the site and not biased toward conditions that are rare,
12 extreme, or unlikely at the site, particularly if the unlikely conditions lead to overly optimistic
13 behavior of the disposal system. Uncertainty in the parameters may also be significant. For
14 instance, permeability may span a broad range of values depending on the soil types (Nazaroff,
15 1992). Therefore, the analysis of uncertainty in significant parameters should consider the
16 range of conditions expected for the disposal site. Partitioning of gaseous radionuclides
17 between phases may also affect transport of radionuclides that are generated in the gas phase.
18 In addition, biological activity and isotopic dilution (i.e., dilution of a radioisotope with stable
19 isotopes of the same element) may also have a significant impact on the transport of certain
20 gaseous radionuclides (e.g., carbon-14) (Bracke and Müller, 2008).

21
22 Changes in cover properties that are responsible for increasing the hydraulic conductivity may
23 also affect the migration of radon-222 through the cover. Licensees can design cover materials
24 to inhibit radon migration, so that radon flux at the surface is reduced by radioactive decay
25 during transport to the surface (NRC, 1984). However, preferential flow paths can develop in
26 clay barriers in conventional covers (Albright et al., 2006a; Albright et al., 2006b). Preferential
27 flow paths may lead to advective transport of radon. Typically radon migration is controlled by
28 diffusion which is dependent on the inter-connected porosity and moisture content of the soil or
29 clay radon barrier (NRC, 1989a). In addition to enhanced diffusive transport, advection may
30 also contribute to significant migration of radon via these preferential pathways (NRC, 1984).
31 NUREG/CR-3395, "Influence of Cover Defects on the Attenuation of Radon with Earthen Cover"
32 states that models for radon migration in cracks are typically designed for simple geometries
33 that do not account for all dynamic processes resulting in a possible underestimation of radon
34 flux (NRC, 1983a). The recommendation from NUREG/CR-3395 is to apply cover design and
35 development methods so as to avoid the formation of defects (i.e., avoid cracks) in light of this
36 uncertainty.

37 **3.2.7 Direct Release**

38
39 Licensees may need to represent the direct release of radionuclides into the environment.
40 Models for direct release estimate the rate of radionuclides released directly to the surface as
41 the result of natural FEPs. Anthropogenic direct releases are considered in the inadvertent
42 intrusion assessment, which is discussed in Section 4.0. Direct releases may be caused by
43 processes such as plant uptake, bioturbation (e.g., burrowing animals), natural disruptive events
44 (e.g., faulting), and geomorphological processes (e.g., erosion). For guidance on consideration
45 of natural disruptive events and geomorphological processes, licensees and reviewers should
46 consult Section 5.0 of this document regarding the demonstration that the performance
47 objective for site stability would be met. Direct release can impact the demonstration that
48 10 CFR 61.41 and 10 CFR 61.42 would be met. Licensees should integrate direct release

1 calculations with other models as necessary, such as with climate and radionuclide transport.
2 Additionally, direct release calculations should consider the long-term evolution of the site
3 environment and its impact on the evolution of the site's geomorphology and ecology. For
4 instance, future climate states may be wetter, leading to increased erosion rates or changes in
5 vegetation or communities of burrowing animals. Erosion or burrowing animals are processes
6 that can lead to direct releases. Licensees may use analog sites with climates similar to the
7 expected future climate for the disposal facility to justify the progression of ecological
8 communities at the disposal site.

9 **3.2.8 Biota Enhanced Release**

10
11 "Biota enhanced release" is defined in this section as the direct and indirect processes that
12 facilitate release of radioactivity from a disposal facility. Damage of an engineered cover by
13 burrowing animals is an example of an indirect effect of biota on performance of the LLW
14 disposal facility. Biotic transport, as defined in Section 3.3.4 of this document, is defined as the
15 transport of radionuclides in the environment via biota after radioactivity is released.
16

17 Biota enhanced release is not usually considered to be a significant pathway in performance
18 assessments. However, the importance of biotic release and subsequent human exposures
19 depends on a variety of factors, including site location, design of the disposal facility, and the
20 wasteforms disposed of at the site. For example, plant uptake and the impact of burrowing
21 animals is much more likely for shallow disposal than for deeper disposal. Therefore, a
22 reviewer evaluating radionuclide release from a site should include consideration of the impacts
23 associated with biotic enhanced release. Current LLW disposal facilities attempt to minimize
24 the impacts of plants and animals by incorporating design features such as engineered cover
25 systems and the use of concrete and steel in the construction of the vaults and waste
26 containers.
27

28 Section 5.9.1, "Background," of National Council on Radiation Protection and Measurements
29 (NCRP) 152, "Performance Assessment of Near-Surface Facilities for Disposal of Low-Level
30 Radioactive Waste," lists numerous references of studies of biotic processes conducted at LLW
31 disposal facilities (NCRP, 2005). The long-term contributions of biotic enhanced release
32 processes, including their impacts on engineered wasteforms and barriers, associated with
33 recent LLW disposal facilities are uncertain. Biotic enhanced release has been observed for a
34 wide variety of contaminant release problems; however, biotic enhanced release is typically not
35 a primary release mechanism.
36

37 A study conducted by McKenzie et al. (NRC, 1982d) identifies and discusses the mechanisms
38 of biotic release and transport and human exposure associated with arid and moist sites. Based
39 on this qualitative analysis, the authors of that study concluded that penetration of buried waste
40 and enhanced release by burrowing animals and plant roots were potentially important
41 mechanisms in the case of waste disposed in trenches. These studies demonstrate that there
42 are three general primary effects of biota on an LLW disposal facility: biotic release, biotic
43 transport (Section 3.3.4), and secondary transport. This section focuses on intrusion and
44 indirect effects which can enhance release through other mechanisms. Depending on the
45 characteristics of the disposal facility and its environmental settings, biota could influence the
46 performance of a disposal system and lead to significant pathways of human exposure.
47

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

17
18 A qualitative assessment of the biotic enhanced release and its contributions to the dose may
19 be sufficient depending on the site, its characteristics, and the characteristics of the waste
20 disposed of at the site. In some cases, biological processes can strongly influence the release
21 of radioactivity from LLW disposal facilities because the near-surface environment is biologically
22 active.

23
24 In addition to direct release (e.g., uptake of radionuclides by deeply rooted vegetation), biota
25 can indirectly enhance release when plants and animals modify the buried waste or the design
26 of the LLW disposal facility in such a way that there is an increased potential for radionuclide
27 release and transport. The following are examples of these processes:

- 28
- 29 • Burrowing animals or root systems develop tunnels or conduits that can enhance the
30 transport of groundwater or increase gaseous release (e.g., bioturbation of a clay layer).
- 31 • Plant roots provide ligands that provide a source for radionuclides to bind, resulting in
32 the formation of soluble radionuclide-organic complexes.
- 33 • Microbial degradation of the wastefoms leads to the enhanced generation of gases or
34 creates waste materials that are more soluble and therefore more easily transported
35 away from the site.
- 36 • Microbial enhanced degradation of waste containers or concrete vaults in a disposal
37 system occurs.
- 38 • A drainage layer is plugged in an engineered cover system.
- 39 • Pedogenic processes can modify the soil properties of an evapotranspiration cover
40 system.
- 41

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

3.3 Radionuclide Transport

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

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

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

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

9
10 Section 2.2 of this document describes general technical considerations applicable to the
11 development and review of a radionuclide transport model for a LLW disposal facility
12 performance assessment. As mentioned previously, licensees and reviewers may also consult
13 NUREG-1573, Section 3.3.6, for further guidance on transport modeling. Section 4.3.4 of
14 NUREG-1854 may assist reviewers by providing technical considerations for acceptable
15 radionuclide transport modeling. The following sections of this document provide specific
16 guidance on aspects of radionuclide transport modeling in various environmental media.

17 **3.3.1 Groundwater Transport**

18
19 A licensee may perform groundwater transport modeling to assess the concentrations of
20 radionuclides transported from LLW disposal facilities through the unsaturated and saturated
21 zones. Groundwater transport is among the most likely processes for radionuclides to be
22 transported from LLW disposal facilities. In addition to being a direct source of exposure to
23 radionuclides, groundwater can transfer radionuclides to other exposure pathways that may
24 ultimately result in doses to members of the public. These transfer processes include
25 discharges to surface water through seeps and springs and vapor releases to the atmosphere.

26
27 A licensee may need to model the migration of radionuclides in groundwater and determine the
28 contribution of the groundwater pathway to the total dose to the average member of the critical
29 group. The complexity of hydrogeologic and geochemical conditions of the site may need to be
30 reduced to form simplified representations of groundwater flow and transport. A licensee should
31 provide a technical basis that the reduction in complexity has not resulted in the loss of
32 information necessary to demonstrate that the performance objectives of Subpart C will be met.

33
34 Development of a groundwater transport model should consider relevant FEPs associated with
35 the site (Section 2.5 presents guidance on FEPs). The characteristics of the wastefoms
36 designed to limit releases of radionuclides as well as the physical characteristics of the site
37 (e.g., hydrogeology, faults, and groundwater flow boundaries) should be considered by
38 licensees. Physical and geochemical processes (e.g., advection, dispersion, diffusion, sorption,
39 precipitation) are the primary phenomena included in radionuclide transport models.

40
41 The transport of radionuclides in groundwater can be affected by many different physical
42 phenomena associated with the hydrogeology of the system, as well as by the physical
43 components (e.g., engineered barriers) associated with the facility. Information on the
44 hydrogeologic characteristics of the site including the stratigraphy, the existence of preferential
45 pathways (e.g., fractures), spatial variations in properties, and anthropogenic features that may
46 affect groundwater flow should be considered by licensees. Processes such as diffusion,
47 mechanical dispersion, and colloid-facilitated transport should be considered. In the case of the
48 unsaturated zone, variations in properties and features such as thickness of unsaturated strata

1 and hydraulic properties can impact water flow. The spatial variation of hydrologic properties of
2 aquifers and aquitards, as well as geologic features (e.g., fractures) and engineered structures
3 (e.g., slurry walls), can influence groundwater flow velocities, gradients, volumes, and estimates
4 of recharge to and discharge from the aquifers associated with the saturated zone. In addition,
5 licensees should consider differences associated with the unsaturated zone and saturated zone.
6 Flow of contaminants in the unsaturated zone may be strongly influenced by discrete features,
7 such as fractures or other heterogeneities. A licensee should provide their site-specific
8 characterization data of the spatial variation in hydrologic properties and geologic features. If
9 site-specific information is not available, the licensee should demonstrate how variability in
10 properties and features was incorporated and evaluated in the radionuclide transport modeling.

11
12 A licensee should evaluate the chemical characteristics of the groundwater and host rocks
13 including sediments. Chemical processes such as sorption, precipitation, ion exchange, and
14 redox reactions can affect radionuclide transport in groundwater. NUREG-1573 (NRC, 2000a)
15 and NUREG-1854 (NRC, 2007a) provide guidance for assessing groundwater transport.
16 Additionally, NCRP has published a summary of processes and parameters applicable to the
17 development of groundwater transport models in the performance assessment for a LLW
18 disposal facility (NCRP, 2005).

19
20 Table 3-1 summarizes site characteristics, physical processes, and geochemical processes that
21 should be considered by licensees when developing groundwater transport models. Reviewers
22 should use Table 3-1 to evaluate the scope of a licensee's radionuclide transport modeling.

23
24 Modeling groundwater transport can be challenging for a variety of reasons. The characteristics
25 and features that introduce challenges include the following:

- 26
27 • the complex interactions of the hydrologic, geologic, physical, and chemical processes
28 associated with the system
- 29 • the site-specific flow and transport characteristics for modeling the initial release from
30 the disposal facility (i.e., source term) through the unsaturated zone to the groundwater
- 31 • the limited availability of site-specific data to describe the FEPs for a specific
32 groundwater system
- 33 • the natural heterogeneity of site characteristics associated with groundwater flow and
34 transport and changes in characteristics over long times
- 35 • numerical analysis techniques may introduce modeling artifacts, such as numerical
36 dispersion, which can bias results

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

46

1 **Table 3-1 List of Parameters and Processes of Concern Associated with the**
 2 **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)

3
 4 A simplified analysis may be acceptable for facilities for which the simplified analysis can be
 5 shown to be clearly conservative or for which the simple model is supported by multiple lines of
 6 evidence, including field tests that demonstrate that the model and its parameters appropriately
 7 represent or bound site conditions. A simplified groundwater modeling approach may be
 8 sufficient to gain an adequate understanding of the FEPs associated with a specific system.
 9 More detailed groundwater flow and transport modeling, however, may be needed to identify
 10 important processes and assess the impacts of uncertainty and variability to support the
 11 simplification of the conceptual groundwater flow system.

12
 13 An important consideration in modeling groundwater flow and transport is the inherent spatial
 14 variability of structural, physical, and chemical properties of the environmental media and the
 15 uncertainty in characterizing the spatial domain. Heterogeneity in flow and transport processes
 16 can vary over many orders of magnitude from the molecule scale to the basin scale (Ledoux
 17 and deMarsily, 1997). Some properties exhibit scale-dependence (e.g., dispersivity)
 18 (Neuman, 1990). When warranted by the significance of the transport pathway, a licensee may
 19 need to include a more explicit representation of the inherent variability. However, it is
 20 challenging to describe the full spectrum of the heterogeneity due to the amount of
 21 characterization that would be needed. Rubin (2003) summarized some approaches (e.g.,

1 estimation, simulation) that licensees may consider for use in representing the inherent
2 variability and assessing its impact on groundwater flow and transport.

3
4 Licensees should demonstrate that the method used to assess groundwater transport does not
5 bias the outcome such that radiological doses to an offsite receptor are significantly
6 underestimated. A possible method to demonstrate this is through comparisons with viable
7 alternative conceptual models of the groundwater flow system that are consistent with the
8 current understanding of the site.

9
10 For the performance assessment of a LLW disposal facility, the parameterization of processes
11 should be made at the scale (spatial and temporal) over which groundwater transport is
12 evaluated. However, measurements of flow and transport parameters on these large scales are
13 often not available or practical. Additionally, smaller scale measurements, such as from
14 laboratory or field tests, can provide useful information to models, but the models can quickly
15 become computationally complex. For instance, performance assessments often represent
16 sorption of radionuclides on soils through the use of a distribution coefficient (K_d). In a
17 groundwater transport abstraction for a disposal facility, this coefficient may be representing the
18 inherent heterogeneities in the soil properties and groundwater chemistry over large spatial
19 scales. In practice, distribution coefficients are often measured in the laboratory or field on a
20 much smaller scale than what is modeled in the performance assessment and may not
21 represent the actual heterogeneities in the groundwater pathway that the radionuclides might
22 encounter. Therefore, licensees should consider approaches to demonstrate the
23 appropriateness of model parameters for the scale of concern for the performance assessment
24 (e.g., upscaling, inverse modeling). The following two sections provide examples of specific
25 issues to consider when evaluating the unsaturated zone and the saturated zone.

26 **3.3.1.1 *Modeling the Unsaturated Zone***

27
28 This section highlights issues specific to the flow and transport of groundwater through the
29 unsaturated zone and the flow and transport modeling that affect the ability of a licensee to
30 develop a defensible performance assessment. Section 4.3.4.2.3 of NUREG-1854 (NRC,
31 2007a) and NCRP-152 (NCRP, 2005) provide a general discussion of the issues that should be
32 covered. Additional details regarding flow and transport in the unsaturated zone appear in other
33 documents, including Bear (1979), Bear and Verruijt (1987), Domenico and Schwartz (1998),
34 Evans et al. (2001), Faybishenko et al. (2000), Freeze and Cherry (1979), Hillel (1980), Looney
35 and Falta (2000), NAS/NRC (2001), Nielsen et al. (1986), and Todd (1980). Documents such
36 as NAS/NRC (1990) and NCRP (1984) discuss unsaturated flow and transport models. NRC-
37 sponsored research related to the characterization and performance confirmation monitoring of
38 the unsaturated zone is included in various references (Meyer et al., 1999; Rockhold, 1999;
39 NRC, 1993b; NRC, 1999b; NRC, 1999c).

40
41 Modeling of flow and transport of radionuclides in the unsaturated zone provides a link between
42 releases from an LLW disposal facility and the saturated zone. Key inputs for a licensee to
43 consider when developing unsaturated zone flow and transport models include the infiltration
44 rate and the release rate of radionuclides from the source; the resulting outputs, flow rate and
45 radionuclide migration, are used as inputs when modeling saturated zone flow and transport.

46
47 Variations in soil characteristics and moisture content in the unsaturated zone as well as the
48 complex relationships between hydraulic head, moisture content, and hydraulic conductivity can

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

17
18 Arid sites may experience high evapotranspiration rates creating a situation where there is no
19 communication or very limited communication between the disposal facility and the water table.
20 This is especially true for the disposal of inventories containing primarily short-lived
21 radionuclides. Modeling this situation is typically more complex than a traditional flow and
22 transport analysis because spatial and temporal variability can more significantly impact the
23 results. For either thin or thick unsaturated zones, discrete features such as fractures or
24 abandoned wells can limit the effectiveness of the unsaturated zone as a barrier. Completion of
25 field tests and analysis of field observations are recommended to reduce the uncertainty
26 associated with discrete features in the unsaturated zone. Tracer studies over a large area can
27 be effective.

28
29 Many of the processes that govern transport of radionuclides in the unsaturated (vadose) zone
30 (i.e., advection, dispersion, and sorption (retardation)) are essentially the same as those that
31 govern transport in the saturated zone. However, since the pore spaces of the vadose zone are
32 only partially filled, the effective hydraulic properties have a nonlinear dependence on soil
33 moisture content. Flow and moisture dependencies are commonly represented with moisture
34 characteristics curves. Moisture characteristics curves can be difficult to define and to use to
35 characterize the spatial variability over the area of a disposal site.

36
37 Because of the nonlinear relationships, flow in the unsaturated zone can be strongly influenced
38 by extreme conditions (e.g., a zone of discrete features such as fractures, wetter years, or
39 seasonal variations). Therefore, it is necessary for a licensee to understand how hydraulic
40 conductivity changes as a function of the amount of moisture and the pressure in the soil. For
41 example, when the fluid pressure is less than the atmospheric pressure, the pressure head is
42 negative allowing suction to occur (Freeze and Cherry, 1979). Additionally, the infiltration rate
43 may vary with time as a result of the intermittent nature of precipitation. It may also vary with
44 the depth of the unsaturated zone, resulting in greater water content closer to the surface and
45 dampening with depth.

46
47 Given these complexities, a graded approach that starts with the simplest and most
48 conservative approach is recommended for licensees. This technique starts with a relatively
49 simple representation of the system - assume homogeneous conditions and no time delay or

1 dilution. Problems may arise with this simple approach for situations in which the unsaturated
2 media are known to be highly structured or fractured, or if it is determined that there is
3 significant time or distance to reach the saturated zone. For these cases, the modeling
4 approach would need to be more complex. In general, a licensee should only include
5 complexity if that complexity can be supported. However, in the iterative modeling process a
6 licensee may need to add complexity to determine if the complexity is significant. If it is, support
7 may need to be developed or a conservative approach may be necessary.

8 **3.3.1.2 Modeling the Saturated Zone**

9
10 In a performance assessment for a LLW disposal facility, a licensee should consider the flow of
11 water through underlying aquifers and the phenomena that influence transport of radionuclides
12 in groundwater. A licensee should have an adequate understanding of the input flux of
13 radionuclides from the unsaturated zone. For example, although an increase in flow velocity
14 into the saturated zone would appear to yield higher concentrations of radionuclides being
15 released to offsite locations or other exposure pathways due to decreased travel time, it also
16 results in a greater volume of water available to dilute radionuclide concentrations slowly
17 percolating into the aquifer from the unsaturated zone. Thus, it is possible that the higher flow
18 rate can actually result in a decrease in radionuclide concentrations. For a licensee to complete
19 a sufficient evaluation of the groundwater transport in the saturated zone requires an
20 understanding of the groundwater velocity field, radionuclide-specific release rates to the
21 saturated zone, and the phenomena that influence the transport of radionuclides in groundwater
22 (e.g., sorption, advection, diffusion, dispersion, and radioactive decay). Ultimately saturated-
23 zone radionuclide concentrations are typically converted to two primary types of doses for
24 receptor scenarios: the groundwater dose resulting from direct ingestion and the groundwater
25 component of the dose resulting from ingestion of foodstuffs grown using contaminated water.
26 Other pathways are possible and may be significant at specific sites though they are less
27 common.

28
29 The velocity field provides a representation of the groundwater flow in the saturated zone.
30 A velocity field, which is a function of location and time, is often derived using indirect, largely
31 unmeasured, spatially variable, or unknown physical properties and boundary conditions that
32 can be interpreted only subjectively. Licensees may develop the velocity field by using a site-
33 specific model of the flow system that has been calibrated using site-specific data on hydraulic
34 head. The hydraulic head can be obtained using monitoring wells and field experiments (e.g.,
35 slug tests). However, the derived velocity field is likely not going to be a unique representation
36 for a specific site, as multiple velocity fields can often be used to describe a site equally well. As
37 a result, licensees should provide justification and support for their assumptions. It is often
38 useful for a licensee to include the uncertainty associated with the calibration and inverse
39 modeling to derive groundwater flow fields in the performance assessment groundwater flow
40 model. Therefore, the significance of the uncertainty can be directly assessed.

41
42 Licensees may describe groundwater flow in the saturated zone using a simplified flow
43 equation, which combines Darcy's Law with the principle of conservation of mass. This
44 approach may be further simplified by assuming a steady-state flow rate and uniform recharge
45 to the aquifer over the spatial domain being considered. However, uncertainties such as the
46 presence of heterogeneities in the system, variable or unknown boundary conditions, and
47 scaling of data obtained from core samples to field conditions need to be evaluated by licensees

1 when using this approach to groundwater flow modeling. A licensee must provide model
2 support for the simplified flow model results.

3
4 Various other phenomena may influence the development of models to represent the transport
5 of radionuclides in groundwater. Radioactive decay is well understood, presuming that there is
6 sufficient understanding of the source term; however, approximations may be required when
7 considering radioactive decay and ingrowth associated with disposal sites containing many
8 radionuclides. For radionuclides with chain decay that results in multiple progeny, the behavior
9 of the progeny in the environment may be substantially different than the behavior of the parent
10 radionuclide (e.g., the K_d for Am-241 may be substantially different from the K_d for Np-237). In
11 cases where a long-lived radionuclide has decay products of radiological significance, selecting
12 the lowest plausible K_d value may not result in the highest estimated dose. A licensee should
13 provide sufficient justification for the use of specific K_d values to evaluate sorption and
14 desorption. Ideally, site-specific K_d values should be used. However, in cases where site-
15 specific values are not available generic values may be assessed. Numerous publications have
16 documented generic values; some even group distribution coefficients according to soil type
17 (Sheppard and Thibault, 1990; Yu et al., 1993). Licensees should use these values with caution
18 as they often include variation between sites but do not include potential measurement errors
19 (e.g., exceeding solubility limits in measurements of sorption parameters). In addition, the
20 measurements in the compilation may have been taken using significantly different techniques.

21
22 Ultimately, a licensee can best treat uncertainties associated with radionuclide transport in
23 groundwater by using multiple conceptual models. This enables a licensee to examine the
24 effects of different credible assumptions and provides a better understanding of which
25 processes are most sensitive and may need to be considered in greater detail.

26 **3.3.2 Surface Water Transport**

27
28 Surface water transport modeling is used to assess the radionuclide concentrations in surface
29 water (e.g., rivers, lakes) at human access locations at or beyond the site boundary. By
30 demonstrating that the requirements for site suitability in 10 CFR 61.50, "Disposal Site
31 Suitability Requirements for Land Disposal," and site design in 10 CFR 61.51, "Disposal Site
32 Design for Land Disposal" are met, it is unlikely that a licensee will estimate that significant
33 amounts of surface water would directly intersect a waste disposal facility. Therefore,
34 radionuclides will likely be transported from a LLW disposal facility via other pathways rather
35 than a surface water pathway. However, radioactivity released to an aquifer may discharge to
36 surface water bodies before contact with or use by the public. Mechanisms by which
37 radionuclides may enter the surface water include groundwater discharge and deposition
38 associated with atmospheric transport, and overland flow (e.g., associated with erosion).

39
40 Licensees should evaluate hydrological and chemical conditions at the site to form simplified
41 representations of surface water flow and transport if surface water transport is a viable
42 exposure pathway for public receptors. Simplified analyses to assess surface water transport
43 may be justified at most disposal facilities sited and constructed according to 10 CFR Part 61
44 requirements. However, some facilities, depending on site-specific conditions, may require
45 detailed consideration of surface water transport. Licensees should demonstrate that the
46 method used to assess surface water transport does not bias the outcome such that radiological
47 doses to an offsite receptor are significantly underestimated. A licensee should consider

1 contributions to surface waters from other environmental media (e.g., groundwater seepage,
2 atmospheric deposition, overland runoff, and erosion).

3
4 Radionuclides that are released to surface waters may be transported by a variety of processes
5 including water flow, sediment transport, and bioturbation (Onishi, 2008). Radionuclides
6 entering surface water systems may remain in solution, be suspended in the water column
7 attached to particulates, or settle to the bottom and become associated with the sediments.
8 Advection and dispersion are typically dominant processes, especially for soluble radionuclides
9 in flowing water. Radionuclides that readily partition to suspended particles or sediments may
10 also be significantly affected by sediment transport processes (e.g., deposition, erosion,
11 bioturbation). Other hydrologic processes, such as turbulence and thermal and density
12 stratification, can also affect the distribution of radionuclides in surface waters. The chemistry of
13 the surface water, rocks, and sediments may affect the speciation or partitioning of
14 radionuclides (e.g., due to sorption, precipitation, ion exchange, volatilization). Licensees
15 should consider these phenomena when developing surface water transport models.
16 Section 3.3.6.2 of NUREG-1573 provides guidance for the assessment of surface water
17 transport (NRC, 2000a). Section 4.3.4.1.2 of NUREG-1854 provides guidance for the review of
18 surface water transport abstractions (NRC, 2007a). Also, NCRP (1996a, 1996b) describes
19 screening models that may be appropriate for many sites to determine whether more detailed
20 modeling may be required. Additionally, NCRP (2005) and Onishi (2008) discuss approaches
21 for modeling the transport of radionuclides in a variety of surface water bodies that may be
22 appropriate depending on site-specific characteristics.

23 **3.3.3 Atmospheric Transport**

24
25 Atmospheric transport models estimate concentrations of radionuclides released to the
26 atmosphere at offsite receptor locations. Section 3.2.6 discusses guidance for assessing the
27 gaseous release of radionuclides (e.g., C-14, I-129, Kr-85, Rn-222, H-3) from the disposal
28 facility to the atmosphere. Licensees may also need to evaluate the transport of particulate
29 releases caused by direct release (e.g., wind erosion), if significant (see Section 3.2.7). Once
30 released, radionuclides can be transported in the atmosphere to locations downwind from the
31 disposal facility where they could contribute a nontrivial fraction of the dose to the average
32 member of the critical group. To evaluate the impacts of gaseous radionuclides downwind from
33 release points, licensees should consider the following FEPs (Crawford, et al., 2008):

- 34
- 35 • source characteristics (e.g., configuration of the release such as the release height from
36 the surface, puff or continuous releases, gaseous or particulate)
 - 37 • atmospheric transport processes (e.g., wind and turbulence)
 - 38 • radionuclide removal mechanisms (e.g., rainfall, wet and dry deposition)
 - 39 • general topography of the land near the disposal facility
- 40

41 Source characteristics listed above include information about the material released as well as
42 the configuration of release. The characteristics of the released material include physical form
43 (e.g., gaseous, particulate), chemical stability in the atmosphere, and radioactive decay. For
44 instance, particles with diameters greater than 10 micrometers may experience significant
45 gravitational settling, and thereby, possibly limited atmospheric transport. The configuration of
46 the release may also be an important consideration. Information on the configuration includes

1 timing and spatial extent. For instance, radioactivity may be released continuously or nearly
2 instantaneously, as well as from a single point or over an area. Atmospheric transport
3 processes listed above include a characterization of the physical processes affecting transport
4 of radionuclides (e.g., advection, dispersion). These processes include movement by wind,
5 represented by wind direction and speed, as well as mechanical and thermal turbulence which
6 can result in mixing caused by eddies. Removal mechanisms listed above include deposition,
7 as gases and particles are deposited on surfaces and possibly removed from the atmosphere.
8 Deposition may result from a variety of processes, both dry and wet, including impingement,
9 electrostatic interactions, chemical reactions, and rainfall. Site topography as well as nearby
10 engineered structures could affect atmospheric transport; licensees should exercise caution
11 when using analog atmospheric transport data for a site-specific evaluation.

12
13 An important consideration in atmospheric transport modeling is the scale of motion in
14 atmospheric processes. Atmospheric processes such as wind direction and speed may vary
15 over a wide range on spatial scales from a kilometer or less to thousands of kilometers, as well
16 as over the course of hours to years. Therefore, the consideration of atmospheric transport
17 processes and their parameterization is a function of the spatial and temporal transport scale of
18 interest. Atmospheric transport from LLW disposal facilities to an offsite human receptor is
19 typically on the order of less than a kilometer to tens of kilometers. Temporal scales of interest
20 for LLW disposal range up to 10,000 years to assess the annual dose to an offsite receptor from
21 releases. Licensees should consider processes consistent with the context of the transport
22 scale, both spatially and temporally. Additionally, input data should be consistent with the scale
23 of transport, both spatially and temporally. For instance, winds may vary in speed and direction
24 with time and height. Therefore, meteorological data to support model parameterization should
25 be consistent with and account for uncertainty and variability over the spatial and temporal
26 scales of interest for the site. Licensees should demonstrate the representativeness of model
27 parameters for the scales of concern for the performance assessment.

28
29 The assessment of the performance of some disposal facilities may require a licensee to
30 evaluate the atmospheric transport of radionuclides associated with particulates. For instance,
31 progeny of gaseous radon are charged and are attracted to atmospheric particles of opposite
32 charge. Key factors for a licensee to consider when evaluating the transport of particulates
33 include: mass loading, resuspension rate, deposition rate, and wind speed. These factors are
34 dependent on site-specific conditions such as soil type, wind distribution, and other
35 meteorological conditions, as well as mechanical disturbances.

36
37 The assessment of the performance of some disposal facilities may require detailed
38 consideration of these processes in the atmospheric transport abstraction, whereas simplified
39 analyses may be justified for other sites and disposal practices. The atmospheric transport
40 models may need to consider these site-specific complexities for those facilities for which
41 licensees take credit for significant delay in radionuclide migration via air transport from the
42 disposal facility to the receptor, those that take credit for significant dilution, those that are relied
43 upon for defense-in-depth protections, as well as those for which there is little model support. A
44 simplified analysis may be acceptable for facilities for which the model can be shown to be
45 clearly conservative or for which the simple model is well supported by multiple lines of
46 evidence, including field tests demonstrating that the model and its parameters appropriately
47 represent or bound site conditions. A simplified atmospheric transport modeling approach may
48 be sufficient to gain an adequate understanding of the FEPs associated with a specific system.
49 More detailed atmospheric transport modeling, however, may be necessary to identify important

1 processes and assess the impacts of uncertainty and variability needed to support the
2 simplification of atmospheric transport. Licensees should demonstrate that the methods used to
3 assess atmospheric transport do not bias the outcome such that radiological doses to an offsite
4 receptor are significantly underestimated.

5
6 NUREG-1573 provides a screening approach to assess whether more detailed consideration of
7 atmospheric transport modeling is required for gaseous radionuclides (NRC, 2000a). Discussed
8 in Section 3.3.6.3.2.1 of NUREG-1573, the approach uses the total gaseous radionuclide
9 release over 1 year and conservative meteorological conditions for wind speed, atmospheric
10 stability, and atmospheric diffusion. However, the licensee should still provide justification for
11 the conservatism of the meteorological assumptions and parameters used. NCRP-152
12 discusses possible approaches for estimating quantities of particulates suspended in the air
13 (NCRP, 2005). An NRC staff-recommended screening approach to evaluate the transport of
14 particulate matter, which is suspended in the air and transported downwind, assumes that the
15 radionuclide concentrations in the atmosphere are equal to the concentrations in the surface soil
16 or other source from which they originated. Section 3.3.6.3.2.2 of NUREG-1573 provides
17 guidance for sites where more detailed analyses may be required. In addition, Crawford et al.
18 (2008), discusses models that have been developed to assess atmospheric transport of
19 radionuclides. Licensees should be aware that the output of the models is dependent on their
20 assumptions and the data to support the parameters. Model selection and parameterization
21 should be consistent with site conditions and supported by field observations, laboratory
22 experiments, and other relevant information.

23 **3.3.4 Biotic Transport**

24
25 This section defines biotic transport as the transport of radionuclides from a disposal facility via
26 biota (NRC, 1982d). Other sections of this document cover the indirect effects of biota on the
27 disposal system, such as damage of an engineered cover by burrowing animals. This biotic
28 transport section does not cover plant uptake or radionuclide movement within the biosphere
29 after radionuclides have been released from the disposal facility via other mechanisms, such as
30 groundwater release. Instead, this section focuses on offsite transport of radionuclides that
31 have been released from the disposal facility by biota. One example of intrusion and active
32 transport involves the Russian thistle (tumbleweed or *Salsola kali*). The long root system (on
33 the order of meters) allows the plant to take up radionuclides from the soil (i.e., biota enhanced
34 release). In autumn, the mature plant dries and detaches from the surface; it is then blown by
35 the wind until it encounters an obstruction (biotic transport). Thus, the plant can cause both
36 vertical and horizontal movement of radioactive material from a disposal site.

37
38 A qualitative assessment of the biotic transport pathway and its contributions to the dose may
39 be sufficient depending on the site, its characteristics, and the characteristics of the waste
40 disposed of at the site. Biotic transport may be the primary transport mechanism at sites
41 without viable water pathways.

42
43 Secondary transport occurs after transfer of radionuclides to biotic sources (i.e., plants and
44 animals) such as the movement of radionuclides within and among the plants and animals
45 associated with the food chain. Examples of processes that transfer radionuclides to biotic
46 sources include overland flow, atmospheric deposition, and use of contaminated groundwater
47 for irrigation. Overland flow can result in the deposition of radionuclides into a surface water
48 body. Once deposited, radionuclides can remain in the water where they may be taken up by

1 animals drinking the water or by plants extracting water through their root systems;
2 radionuclides settling to the bottom sediments may be extracted by plant root systems.
3 Additionally, radionuclides released to the atmosphere may accumulate on plant surfaces or in
4 the soil by wet or dry deposition and eventually become incorporated in plants and animals.
5 The groundwater transport pathway is often the most common means for transporting
6 radionuclides from LLW disposal facilities to the surrounding biota since the waste is buried
7 below ground. Secondary transport allows for additional displacement of radionuclides
8 available to the biota. Food chain activities, such as the consumption of fruits containing
9 radionuclides by animals, are an example of secondary transport. Upon entering the food
10 chain, processes such as ingestion and excretion provide a means for the movement of
11 radionuclides throughout the system. Secondary transport is evaluated using modeling of the
12 biosphere.

13 **3.4 Biosphere**

14
15 For the purposes of a performance assessment, the biosphere is the physical environment
16 accessed by a receptor. The objective of biosphere modeling is to calculate estimates of
17 radiological exposures to humans, in terms of the average member of the critical group, from
18 radionuclide releases from the disposal site over time and space. Licensees can then use the
19 resultant exposures for comparison with the 10 CFR 61.41 performance objective. The
20 biosphere includes the transfer of radionuclides through the human food chain and human
21 dosimetry, including characteristics and lifestyles of the human receptors. There are two
22 specific areas to consider in the assessment of doses to humans. First, the mechanism of
23 radionuclide transfer through the biosphere to humans needs to be identified and modeled.
24 This is often termed pathway analysis. Second, the dosimetry of the exposed individual must
25 be modeled. This is termed the dose assessment. Section 3.3.7 of NUREG-1573 discusses
26 pathway analysis and dose assessment in detail and provides acceptable approaches for
27 performing these analyses (NRC, 2000a).

28
29 The pathways analysis and dose assessment require the development of receptor scenarios
30 that describe the activities in which an average member of the critical group would be engaged.
31 Receptor scenarios typically involve input parameters to describe the transport and exposure to
32 radionuclides that can be generally classified as behavioral, metabolic, or physical. Behavioral
33 parameters collectively describe the behavior hypothesized for the average member of the
34 critical group. The behavior is normally consistent with local practices (e.g., time spent
35 gardening, vegetable consumption rates). Metabolic parameters also describe the exposed
36 individual, but generally address involuntary physiological characteristics of the individual (e.g.,
37 breathing rates, factors converting intake of unit activity to dose by radionuclide). Physical
38 parameters collectively describe the physical characteristics of the site (e.g., geological,
39 hydrologic, geochemical, ecological, and meteorologic inputs). Section 4.3.5 of NUREG-1854
40 provides guidance on behavioral, metabolic, and physical input parameters used in the
41 biosphere modeling (NRC, 2007a).

42
43 For estimating the performance of a land disposal facility far into the future, licensees may need
44 to consider changes to the physical environment over time and the impact that may have on
45 receptor behaviors or physical parameters of the site. For instance, at a site that is currently
46 inhospitable to gardening because of a harsh environment, a licensee may need to consider the
47 evolution of the environment over time. If future climates are expected that may significantly
48 change human behaviors, licensees may need to consider behaviors conducted at other sites

1 that are currently analogous to the expected climate. Because metabolic parameters are
2 involuntary and future evolution of humans is difficult to estimate, licensees should rely on
3 current information regarding metabolic parameters and do not need to forecast changes to
4 metabolic parameters over long timeframes.

5
6
7

4.0 INADVERTENT INTRUSION

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

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

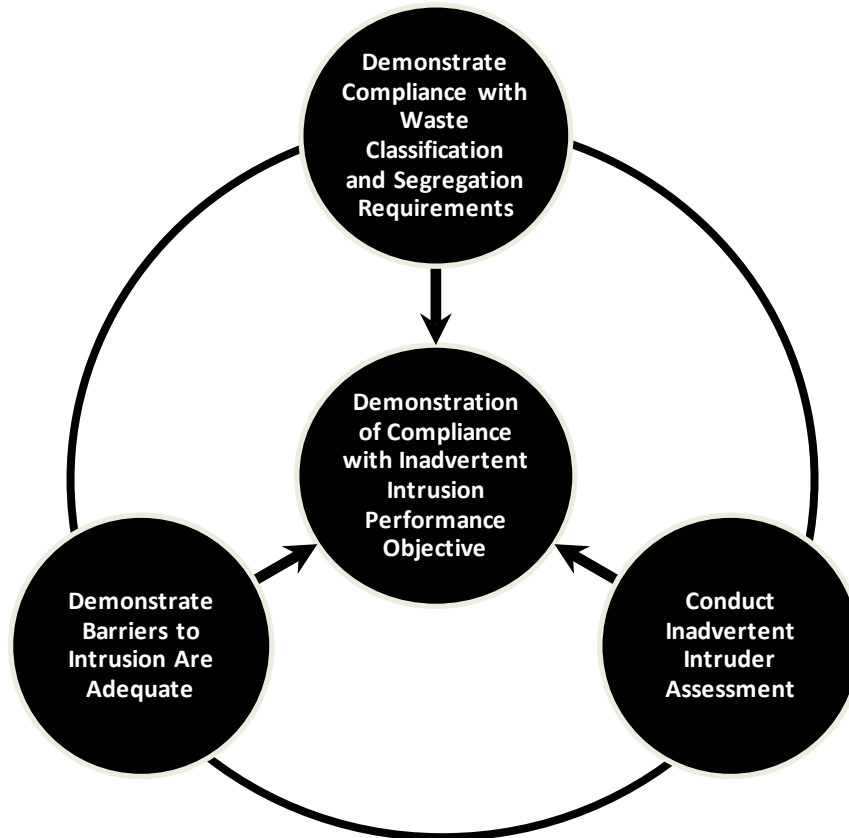


Figure 4-1 Technical Analyses Required to Demonstrate Compliance with the 10 CFR Part 61 Performance Objective for the Protection of Individuals from Inadvertent Intrusion

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

8 **4.1 Waste Acceptance Requirements**

9
10 Requirements for waste acceptance for land disposal appear at 10 CFR 61.58. The regulations
11 require applicants to identify (i) criteria for the acceptance of waste for disposal, (ii) acceptable
12 methods for characterizing the waste, and (iii) a program to certify that waste meets the
13 acceptance criteria prior to receipt at the disposal facility. Section 9.0 of this guidance
14 document describes acceptable approaches for demonstrating compliance with the waste
15 acceptance requirements specified at 10 CFR 61.58. Licensees who limit disposal to waste
16 under approved waste acceptance plans satisfy this requirement.

17
18 Reviewers should coordinate the review of whether the waste acceptance criteria will be met
19 with reviews of the waste acceptance requirements. See Section 9.0 for guidance on reviewing
20 compliance with the waste acceptance requirements. This review should include (1) an
21 assessment of whether the waste acceptance criteria are adequate, and (2) confirmation that
22 the licensee has identified acceptable methods for waste characterization and has an adequate
23 waste certification program to demonstrate that the acceptance criteria are met.

24 **4.2 Inadvertent Intrusion Barriers**

25
26 Intruder barriers are designed to inhibit contact with the waste (e.g., Class C waste) that is
27 expected to present a hazard to an inadvertent intruder should institutional controls fail. The
28 barriers ensure that radiation exposures to an inadvertent intruder will be within the limits of the
29 performance objective specified at 10 CFR 61.42. Intruder barriers are distinct from institutional
30 controls, yet complement the protection provided by institutional controls as a measure of
31 defense-in-depth. An intruder barrier is defined as (1) a sufficient depth of cover over the waste
32 that inhibits contact with waste and helps to ensure that radiation exposures to an inadvertent
33 intruder will meet the performance objective, or (2) engineered structures that provide
34 equivalent protection to the inadvertent intruder. Section 61.52(a)(2) requires that wastes
35 designated as Class C must be disposed of with sufficient depth (i.e., minimum of 5 meters
36 below the surface of the cover) or intruder barriers designed to protect for at least 500 years.
37 Licensees who elect to develop waste acceptance criteria from the results of the technical
38 analyses (i.e., 10 CFR 61.13) may also need to identify certain waste streams that require
39 intruder barriers to ensure protection of an inadvertent intruder. The inadvertent intruder
40 assessment should be used to demonstrate that the intruder barrier can limit exposures for at
41 least 500 years when used for Class C waste, or as long as necessary to limit exposures to an
42 inadvertent intruder to the limits prescribed in 10 CFR 61.42. The assessment should look at
43 site-specific conditions such as the length of time over which the disposed waste presents a
44 significant hazard to an inadvertent intruder. Further, the inadvertent intruder assessment may
45 identify the need for adequate barriers to demonstrate protection of inadvertent intruders from
46 disposal of other waste (e.g., Class A and B waste) based on site-specific conditions.

47

1 While both intruder barriers and institutional controls can limit contact with the waste, they use
2 different mechanisms. Institutional controls are used to limit intruder access to, or use of, the
3 site for a period of time following transfer of the disposal site to the owner and cannot be relied
4 on for more than 100 years under 10 CFR 61.59, "Institutional Requirements." An institutional
5 control program includes legal mechanisms (e.g., land use restrictions), environmental
6 monitoring, periodic surveillance, minor custodial care, or other requirements as determined by
7 the Commission as well as the administration of funds to cover the costs of these activities.
8

9 Intruder barriers are passive features of the disposal facility and site that are intended to
10 enhance a disposal facility's ability to protect an inadvertent intruder who may engage in normal
11 activities or other reasonably foreseeable pursuits that are consistent with activities in and
12 around the site at the time of closure. Intruder barriers may include sufficient depth of cover
13 over the waste or engineered structures (e.g., reinforced concrete vaults) that can provide
14 protection to the inadvertent intruder. For more mobile radionuclides that could affect the
15 intruder through ground water exposure pathways, intruder barriers may also include features
16 that limit the potential release and transport of radionuclides (e.g., the wasteform).
17

18 Section 61.12(b) requires that the specific technical information describing the land disposal
19 facility include design features related to inadvertent intrusion. As part of this description,
20 licensees should identify intruder barriers and describe their capabilities in terms of inhibiting
21 contact with disposed waste and ensuring that radiation exposures will meet the performance
22 objective at 10 CFR 61.42. Because of the wide range of radioactive materials at disposal
23 facilities, the regulations and this guidance are not prescriptive as to the acceptability of site-
24 specific intruder barriers. Because of this flexibility and because intruder barriers are site-
25 specific, it is important for licensees to clearly and completely document the description of the
26 barriers' capabilities and the supporting technical basis.
27

28 The information supporting the barriers' capabilities should be provided for the time period over
29 which each barrier performs its intended function, including any potential changes to the barrier
30 during the compliance period. These capabilities, including uncertainties, should be consistent
31 with the performance attributed to the barriers in the analyses performed in the inadvertent
32 intruder assessment. The NRC staff will use information gained from the inadvertent intruder
33 assessment, independent calculations, and other appropriate quantitative analyses to confirm
34 each barrier's capabilities. The NRC staff will confirm that the technical bases for barrier
35 capabilities are consistent with the technical bases for the inadvertent intruder assessment. In
36 some cases, the barrier capabilities may differ from the information used to support the intruder
37 assessment; for example, the intruder assessment may have conservatively ignored the
38 benefits of the intruder barrier.
39

40 The functionality and robustness of the barriers will be determined using the risk-informed
41 graded approach described in Section 4.2.1 and will be evaluated on a site-specific basis for
42 each license application. However, the general framework that a licensee should consider will
43 not vary from licensee to licensee; only the depth and breadth of information supplied to
44 demonstrate the capabilities of the intruder barriers may vary. The guidance that follows
45 provides the general framework a licensee should consider for intruder barriers.
46
47

1 **4.2.1 Risk-Informed Approach to Evaluating Intruder Barriers**

2
3 Licensees are encouraged to use a risk-informed approach to select, design, and provide a
4 technical basis for the intruder barrier(s) at a specific site. The approach is defined by the
5 hazard level and likelihood of hazard occurrence. More robust barriers and additional bases for
6 barrier capability should be provided for higher risk disposal facilities compared to lower risk
7 facilities. The use of the term “risk” with respect to intruder barriers means the potential for risk;
8 the analyses and resultant actions should ensure that high risks are not realized by a member of
9 the public. The NRC would consider disposal facilities where the potential intruder hazards may
10 be large as high risk. For instance, the NRC would consider a disposal facility with unmitigated
11 doses following the institutional control period greater than 50 mSv/yr (5,000 mrem/yr) to be
12 high risk.

13
14 Licensees should assess the significance of each intruder barrier to mitigate exposures to
15 inadvertent intruders. Any intruder barrier that reduces unmitigated doses less than or equal to
16 5 mSv/yr (500 mrem/yr) to smaller doses is of low significance. A barrier that reduces
17 unmitigated doses ranging between 5 to 50 mSv/yr (500 to 5,000 mrem/yr) to less than
18 5 mSv/yr (500 mrem/yr), and results in a relative reduction of 50 percent or more, is of moderate
19 significance. A barrier that reduces unmitigated doses greater than 50 mSv/yr (5,000 mrem/yr)
20 to less than 5 mSv/yr (500 mrem/yr) is of high significance. Licensees should provide a
21 technical basis for the capabilities of the barriers commensurate with their significance in
22 mitigating inadvertent intruder exposures. The technical basis should evaluate the time period
23 over which each barrier performs its intended function including any changes during the various
24 periods of performance (i.e., compliance, protective assurance, and performance periods).

25
26 Reviewers will use insights from a licensee’s understanding of each barrier’s capabilities as well
27 as independent analyses to focus reviews on the technical basis supporting the capabilities of
28 significant barriers to limit contact with the waste and their integration in the inadvertent intruder
29 assessment. Section 4.3 discusses guidance on the inadvertent intruder assessment.

30 **4.2.2 Technical Basis for Intruder Barrier Capabilities**

31
32 There is significant uncertainty concerning the estimation of service life and long-term
33 degradation of intruder barriers. This section provides guidance on the main elements of
34 information that should be provided to support the technical basis for the evaluation of intruder
35 barrier capabilities, including the following:

- 36
37
- 38 • a full description of the design, features, and functionality of the intruder barriers
 - 39 • a full description of the site and environmental conditions an intruder barrier would be exposed to
 - 40 • a description of potential degradation mechanisms including consideration of combined and synergistic effects resulting from the service environment expected for the barriers
 - 41 • a description of the suitability of selected numerical models, if used, for the estimation of intruder barrier capabilities
 - 42 • an estimation of uncertainty in parameters and models used in the assessment of barrier capabilities and the design of intruder barriers
 - 43
 - 44
 - 45

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

6
7 The capabilities of some intruder barriers may not be amenable to validation in the traditional
8 scientific sense because of the long time periods involved. Therefore, licensees should provide
9 multiple lines of evidence particularly, though not exclusively, to support barrier capabilities
10 beyond 500 years. As discussed in Section 2.2.3, model support can come in many different
11 forms, including but not limited to analogs, laboratory experiments, field experiments, formal and
12 informal expert judgment, and engineering calculations to demonstrate the reasonableness of
13 the results (e.g., hand calculations when numerical models are used). The level of model
14 support should be commensurate with the relative significance of the barriers in protecting the
15 inadvertent intruder. Section 2.2.3 presents more detail on model support.

16
17 During the operational, postclosure observation and maintenance, or institutional control periods
18 monitoring may be needed to verify the capabilities of intruder barriers. This monitoring involves
19 both monitoring aspects of the environmental system surrounding the disposal facility and
20 monitoring the performance of the facility itself. Nondestructive monitoring technologies that
21 include designed and emplaced sensors are preferred to conventional post-failure monitoring.
22 To the extent practicable, intruder barriers should be designed to support and simplify
23 monitoring and maintenance.

24
25 Reviewers should use information from a licensee's description of intruder barrier capabilities to
26 focus their review of the adequacy of the technical bases. Reviewers should confirm that the
27 technical bases are commensurate with the significance of each barrier's capability and the
28 associated uncertainties. Based on their reviews of the inadvertent intruder assessment,
29 reviewers should confirm: (1) the consistency of the technical basis with the intruder
30 assessment and (2) the quality and completeness of the technical basis for the barrier
31 capabilities.

32 **4.2.3 Use of Engineered Intruder Barriers**

33
34 If an engineered intruder barrier is used at a disposal facility, only the barrier's passive
35 performance to inhibit contact with the waste and limit radiological exposures (i.e., performance
36 of the barrier without monitoring, inspection, and maintenance) should be credited in the intruder
37 assessment to demonstrate compliance with the performance objective at 10 CFR 61.42. The
38 assessment of the capabilities of the engineered intruder barrier should consider the
39 reasonableness of a breach and the potential degradation of the barrier over time because
40 monitoring and maintenance cannot be relied on beyond the period of institutional control.
41 Licensees can find additional information about intruder barriers in:

- 42
43 • NUREG-1757, Revision 1, Volume 2, Section 3.5.4 and Appendix P (NRC, 2006).
44 These sections discuss degradation mechanisms and capabilities of common
45 engineered barriers in greater detail.

- 1 • NUREG-1757, Revision 1, Volume 2, Section 3.5.5. This section summarizes existing
2 guidance and references that may have some relevance to the application of engineered
3 intruder barriers at disposal facilities.
- 4 • NUREG/CP-0195 (NRC, 2011a). This document includes reference material and
5 electronic information sources in the appendices.
6

7 Other reasonably foreseeable disruptive events caused by humans or natural events and
8 processes should be evaluated, and uncertainty in projecting the passive performance of the
9 barriers into the future should be considered (see Example 4.1). For example, waste and
10 disposal facilities might also be subject to instability because of waste characteristics (e.g.,
11 differential settling caused by voids in the waste) or facility design (e.g., long-term physical
12 instability of covers). Subsidence could have the following effects on an engineered surface
13 cover: small depressions forming on the cover, differential settlement causing an uneven cover
14 surface, stress cracks forming on the cover surface, and open voids in the cover, each of which
15 could reduce the depth of cover to an insufficient thickness.
16

Example 4.1

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

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

17
18
19
20 Frequently, engineered surface covers rely on vegetation to resist erosion. The probability that
21 the vegetation cover will deteriorate, due to future drought or disease, is dependent on the
22 hardiness and diversity of plants established on the cover. Fires, severe storms, and ecological
23 succession, due to changing temperature and precipitation, could influence the ability of the
24 vegetation to resist wind and water erosion and maintain a sufficient depth of cover over the
25 waste. Over long periods of time, a minimum erosion rate can amount to a substantial
26 thickness of cover loss (e.g., a 0.5 millimeter (mm)/yr rate will reduce a cover’s thickness by half
27 a meter in 1,000 years).
28
29

4.3 Inadvertent Intrusion Assessment

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

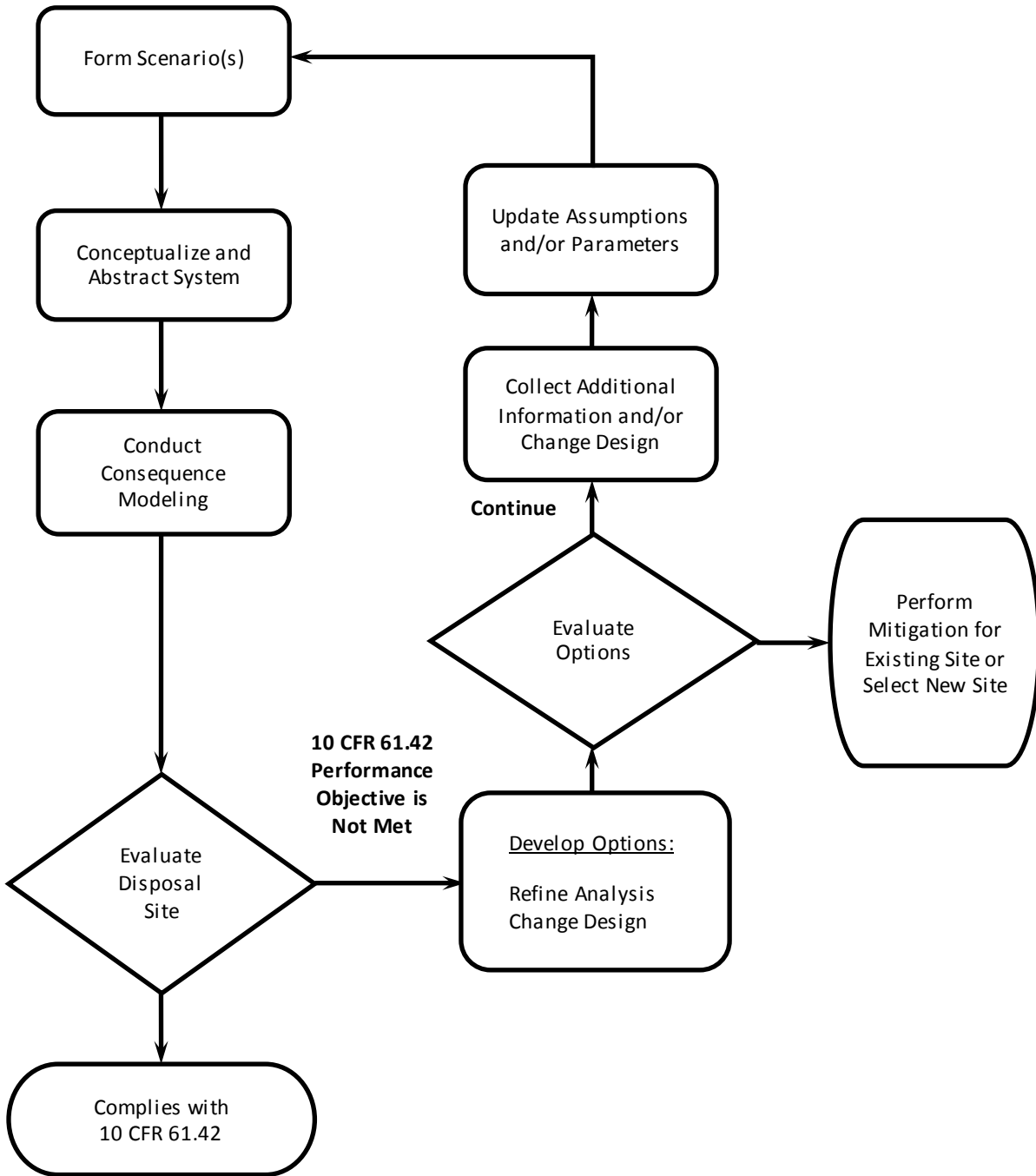
The process for conducting an inadvertent intruder assessment, as shown in Figure 4-2, is similar to the process for conducting a performance assessment in that it is designed to evaluate the following questions, often referred to as the risk triplet:

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

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

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

1



2

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

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

7
8 Further, there is no scientific basis for quantitatively predicting the nature or probability of a
9 future disruptive human activity over long timeframes. This is in contrast to a natural process for
10 which a scientific basis may be developed to support a probability of occurrence. Therefore, an
11 inadvertent intruder assessment does not consider the probability of inadvertent intrusion
12 occurring. Rather, the assessment assumes that reasonably bounding receptor scenarios occur
13 and evaluates the radiological consequences that could be experienced by inadvertent intruders
14 should institutional controls or societal memory be lost (NCRP, 2005).

15
16 The approach to evaluating the first two questions of the risk triplet is an important difference
17 between an inadvertent intruder assessment and a performance assessment and a key reason
18 why the regulations in 10 CFR Part 61 treat these two types of assessments separately.
19 Intruder assessments qualitatively consider the likelihood of a disturbance of the disposal site
20 induced by human intrusion after a loss of institutional control for the reasons mentioned in the
21 preceding paragraph. In contrast, offsite exposures to the general population are driven by
22 natural processes, such as those evaluated in a performance assessment, and could occur at
23 any time after disposal. The performance assessment does not assume that institutional
24 controls or societal memory would be lost (NCRP, 2005). Performance assessments can,
25 therefore, quantitatively evaluate the likelihood of natural events or processes and their effect on
26 the performance of a disposal facility to limit radiological consequences to members of the
27 public beyond the site boundary. The intruder dose assessment is more strongly tied to specific
28 future human behaviors.

29
30 Given the qualitative assumption that inadvertent intrusion is unlikely, albeit possible, because
31 of the presence of required institutional controls, a secondary objective of the assessment is to
32 provide insights that support additional site-specific design and control measures to preclude
33 the intrusion or to limit radiological impacts to acceptable levels should an inadvertent intrusion
34 occur. The additional measures could include site-specific inventory limits or other mitigation
35 techniques such as additional intruder barriers or enhanced disposal practices. See Section 7.0
36 of this document for additional guidance on defining inventory limits based on the results of the
37 technical analyses, including the inadvertent intruder assessment.

38
39 As with the performance assessment, scenario analysis and model abstraction are also key
40 attributes of an inadvertent intruder assessment. Scenario analysis identifies, screens, and
41 constructs scenarios from relevant FEPs for the disposal facility. For an intruder assessment,
42 the formation of scenarios is focused on identifying reasonably foreseeable activities that an
43 inadvertent intruder might engage in on the site (i.e., receptor scenarios). In the near term,
44 licensees can assess reasonably foreseeable human activities based on site-specific conditions.
45 However, future human activities are uncertain at longer times. Therefore, 10 CFR Part 61
46 requires that licensees assess normal activities, such as agriculture or dwelling construction, or
47 pursuits that are consistent with activities in and around the site at the time of closure to limit
48 excessive speculation about future human activities far into the future regardless of whether the

1 intruder activities and the potential pathways of radiological exposure are likely to be affected by
2 features and processes relating to or affecting the facility design and site characteristics over
3 the various periods of performance (e.g., the presence of intruder barriers and their degradation,
4 future climate conditions). Section 2.5.3 discusses methods to identify and screen FEPs for the
5 compliance and protective assurance periods. The approaches are also generally appropriate
6 for the inadvertent intrusion assessment.

7
8 Reviewers should use insights drawn from the review of the intruder barrier analysis (see
9 Section 4.2) to focus their review on topics within the intruder assessment that are important to
10 inhibiting contact with the waste or ensuring that potential radiation exposures to an inadvertent
11 intruder will meet the 10 CFR 61.42 performance objective. The following sections provide
12 guidance related to the process for conducting site-specific inadvertent intrusion assessments.
13 Section 4.3.1 provides guidance on forming receptor scenarios for use in the assessments.
14 Section 4.3.2 provides guidance related to specific aspects of modeling radiological
15 consequences for assumed inadvertent human intrusion. When reviewing a licensee's
16 inadvertent intruder assessment, reviewers should also consult Section 2.0 for guidance on
17 general considerations regarding scenario analysis, model abstraction, and performance
18 assessment that were highlighted in the preceding paragraphs. Section 9.0 also discusses
19 other considerations related to developing waste acceptance criteria from the technical analyses
20 (e.g., using the information from intrusion assessments to establish site-specific measures to
21 limit radiological impacts if inadvertent intrusion occurs).

22 **4.3.1 Receptor Scenario Analysis**

23
24 In developing 10 CFR Part 61, the NRC staff recognized that it is unlikely, though possible, that
25 an individual will occupy a site after closure because of the presence of institutional controls.
26 10 CFR Part 61 does not specify that a particular intrusion scenario be used in the assessment
27 to demonstrate compliance with the performance objective for protection of inadvertent
28 intruders. Rather, the criteria are performance-based. Thus, various methods, both generic
29 and site-specific, are available to licensees, to demonstrate compliance with the criteria.

30
31 Scenario analysis addresses the following questions pertinent to inadvertent intrusion:

- 32
- 33 • What human activities are reasonably foreseeable in the vicinity of the land disposal
34 facility?
- 35 • How can an intruder unknowingly come in direct contact with the disposed waste or be
36 exposed to its radiation?
- 37 • How does the radioactive material move through the environment on the site?
- 38 • What are the inadvertent intruder's habits that will determine exposure?
- 39

40 Intruder receptor scenarios are defined as reasonable sets of activities related to the future use
41 of the site. Therefore, receptor scenarios describe potential future land uses, human activities,
42 and behavior of the engineering design and natural setting. In most situations, possible
43 scenarios for intruders to interact with or be exposed to radiation from the disposed waste are
44 numerous. The criteria in 10 CFR Part 61 do not require an investigation of all possible receptor
45 scenarios; their focus is on reasonably foreseeable activities of the inadvertent intruder.
46 Licensees do not need to assess inadvertent intruder activities that are considered implausible

1 because of persistent physical constraints at the site. The inadvertent intruder is defined in
2 10 CFR 61.2 as "...a person who might occupy the disposal site after closure and engage in
3 normal activities, such as agriculture, dwelling construction, or other pursuits in which the
4 person might unknowingly expose the person to radiation from the waste included in or
5 generated from a disposal facility." Assessment of receptor scenarios for an inadvertent
6 intruder should focus on those activities from which the inadvertent intruder would reasonably
7 be expected to receive the greatest exposure to radiation from the waste. Because of the
8 uncertainty in human activities far into the future, the NRC staff recommends a suite of generic
9 receptor scenarios that are associated with normal activities, described in Section 4.3.1.1, to
10 represent reasonably foreseeable inadvertent intruder activities. Licensees are also permitted
11 to use site-specific scenarios based on other reasonably foreseeable pursuits that are
12 consistent with activities in and around the site at the time of closure to limit speculation about
13 future human activities. Guidance on developing site specific scenarios is discussed in Section
14 4.3.1.2. These sections use a number of different terms describing receptor scenarios. Table
15 4-1 includes a description and comparison of these receptor scenario terms.

16
17 The definition of receptor scenarios and the intruder assessment can be generic or site-specific.
18 Regardless of the specific method used to develop receptor scenarios, the licensee should
19 provide sufficient justification for its approach. Licensees may use generic receptor scenarios
20 similar to those described in NUREG-0782 (NRC, 1981a) with site-specific waste streams, or
21 they may develop site-specific receptor scenarios to evaluate site-specific waste streams. Site-
22 specific receptor scenarios may be developed by modifying the exposure pathways included in
23 the generic receptor scenarios or may be constructed based on waste characteristics, disposal
24 practices, site characteristics, and, when appropriate, projected land use.

25
26 The NRC staff continues to view the generic receptor scenarios as reasonably conservative for
27 estimating potential radiological exposures to an inadvertent intruder while limiting excessive
28 speculation about future human activities. These receptor scenarios are normal activities that
29 humans typically engage in, in a variety of environments, and they contain a nearly
30 comprehensive set of exposure pathways reflecting the generic nature of the original analysis
31 for the development of 10 CFR Part 61 (NRC, 1981a). Licensees may use the generic receptor
32 scenarios described in Section 4.3.1.1 in an intruder assessment to demonstrate compliance
33 with 10 CFR 61.42 for site-specific waste streams. However, in some cases generic receptor
34 scenarios may need to be modified based on site-specific conditions (e.g., waste streams,
35 facility designs, or environmental conditions) to demonstrate compliance with the inadvertent
36 intruder performance objective.

37
38 Depending on the method used, licensees should provide justification for their selections. For
39 some licensees, this may require minimal site-specific data to support the assumptions inherent
40 in the generic receptor scenarios or for removal of specific exposure pathways. Other licensees
41 may need to thoroughly investigate and justify the appropriateness of the selected receptor
42 scenarios, which may include an evaluation of alternate receptor scenarios. If a licensee
43 creates a receptor scenario based on site-specific conditions, they should provide transparent
44 and traceable documentation of the justification for each assumption used in developing the
45 receptor scenario (e.g., justify the inclusion (or exclusion) of a particular exposure pathway).

1
2
3

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

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

4
5

1 **4.3.1.1 Generic Intruder Receptor Scenarios**
2

3 The NRC used a limited number of generic scenarios to inform the development of the
4 10 CFR Part 61 waste classification criteria (NRC, 1981a, 1982b, 1986a). The receptor
5 scenarios involve both direct and indirect contact with disposed waste through consumption of
6 contaminated food as well as receptor scenarios involving a single, acute exposure and
7 scenarios involving long-term, chronic exposure. The NRC used the direct contact receptor
8 scenarios to develop the 10 CFR Part 61 waste classification and segregation criteria (NRC,
9 1981a, 1982b) and later, to update the analysis (NRC, 1986a). The receptor scenarios selected
10 were hypothetical constructs intended to provide reasonable bounds on the exposure of
11 inadvertent intruders to radiation from the LLW; these receptor scenarios helped establish waste
12 classification criteria to be applied at all licensed disposal sites. Loss of institutional control is
13 not expected, but the long-term integrity of the controls cannot be ensured, as the control is
14 primarily derived from records, markers, and government processes and actions, all of which
15 may not be durable over many generations.
16

17 Three direct contact receptor scenarios involve acute exposures, one direct-contact receptor
18 scenario involves chronic exposures, and one groundwater receptor scenario involves chronic
19 exposures as discussed below:
20

- 21 (1) intruder-construction, in which the intruder receives acute exposures while excavating
22 into disposed waste during construction of a dwelling or building
- 23 (2) intruder-discovery, a variant of the intruder-construction scenario, in which the intruder
24 recognizes the presence of waste during excavation and ceases activity
- 25 (3) intruder-drilling, in which the intruder receives an acute exposure while drilling through
26 the waste to install a well
- 27 (4) intruder-agriculture, in which an intruder receives chronic exposures following
28 construction of a dwelling built in the intruder-construction scenario
- 29 (5) intruder-well, in which an intruder is chronically exposed to contaminated groundwater
30 while living on the disposal facility site
31

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

34 **4.3.1.1.1 Intruder-Construction and Intruder-Discovery Receptor Scenarios**
35

36 The intruder-construction receptor scenario involves the construction of a dwelling directly
37 above the disposed waste. During construction activities, workers are assumed to come in
38 contact with some of the waste (e.g., during excavation of a basement). Some of the waste is
39 also assumed to be dispersed into the air by the excavation and emplaced onto the immediate
40 area around the dwelling's foundation. Exposures are estimated for pathways listed in
41 Table 4-2, including inhalation of contaminated dust, exposure to direct gamma radiation from
42 standing on contaminated soil and being immersed in a contaminated dust cloud, and ingestion
43 of contaminated dust or food on which contaminated dust has deposited.
44

1
2
3

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		•			•	•	•	

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

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

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

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

13 4.3.1.1.2 *Intruder-Drilling Receptor Scenario*

14
15 The intruder-drilling receptor scenario is a variant of the intruder-construction scenario that was
16 developed in an update to the initial impacts analysis (NRC, 1986a). The intruder-drilling
17 scenario assumes that, in order to build the dwelling, as in the intruder-construction scenario,
18 the intruder must first install a well to secure an adequate water supply for living needs. During
19 drilling activities, the drilling crew is assumed to inadvertently drill through the waste, bringing it
20 up to the surface in the drill cuttings. If resistance is encountered (e.g., from resistant intruder
21 barriers) during drilling, the crew is assumed to simply move a few yards horizontally to a new
22 location and drill a second borehole. Exposures are estimated for pathways listed in Table 4-2
23 and include exposure to direct gamma radiation from standing in the vicinity of the borehole,
24 where drill cuttings collect, or a mud pit if drilling fluids are used. Because this receptor scenario
25 is limited to drilling activities, release and subsequent exposure occur for a very limited period of
26 time sufficient to complete drilling activities (i.e., typically less than a day). Though a mud pit
27 was evaluated in the initial analysis, current practices vary (e.g., drill cuttings are sometimes
28 spread on the surface). The licensee should justify the assumed cuttings management
29 practices.

30
31 Exposures are estimated for pathways similar to those evaluated in the intruder-construction
32 scenario and are listed in Table 4-2. The exposure pathways include inhalation of contaminated
33 dust from drilling, exposure to direct gamma radiation from standing in the vicinity of the
34 contaminated drill cuttings, being immersed in a contaminated dust cloud, and ingestion of
35 contaminated dust or food on which contaminated dust is deposited. The primary difference
36 between this receptor scenario and the intruder-construction scenario, other than exposure
37 time, is the volume of waste exhumed. The receptor scenario assumes that drilling is performed
38 to supply water for living needs for a single dwelling. The volume of material exhumed is limited
39 to the dimensions of the borehole rather than the dimensions of the dwelling footprint.

40 4.3.1.1.3 *Intruder-Agriculture and Intruder-Well Receptor Scenarios*

41
42 The intruder-agriculture receptor scenario involves an individual or individuals living in the
43 dwelling constructed in the intruder-construction scenario. Exposure pathways for the intruder-
44 agriculture scenario, given in Table 4-2, include those considered for the intruder-construction
45 scenario in addition to consumption of (1) food grown in the contaminated soil, (2) animals that
46 consumed contaminated fodder, and (3) contaminated animal products (e.g., milk and eggs).

47

1 The intruder-agriculture scenario is assumed to be possible only if the waste has been
2 degraded to a form that is indistinguishable from soil. The length of time that the individuals
3 would spend in the contaminated area would be greater for this receptor scenario than for the
4 former intruder-construction scenario because the former scenario is only concerned with
5 exposures to the intruder during construction activities.
6

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

20 4.3.1.1.4 *Criteria for Selecting Generic Receptor Scenarios*

21

22 Licensees may adopt the generic receptor scenarios described in Section 4.3.1.1 to
23 demonstrate compliance if the facility's design, operation, and site are suitable for their use.
24 The scenario used to demonstrate compliance with the performance objective should consider
25 the greatest reasonably foreseeable dose to the inadvertent intruder. Because of the
26 reasonably conservative nature of the generic-receptor-scenarios approach, the estimated
27 radiological exposures are anticipated to be greater than estimates using site-specific receptor
28 scenarios because the generic receptor scenarios usually contain a nearly comprehensive
29 number of exposure pathways. Use of the generic receptor scenarios may save licensees time
30 and effort by reducing the amount of site characterization, modeling analysis, and reviews
31 needed compared to using a site-specific receptor scenario.
32

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

- 36
- 37 • characteristics of the disposal site, such as the presence of adequate water
- 38 • facility design, particularly the expected long-term capabilities of engineered intruder
39 barriers
- 40 • disposal practices, such as waste emplacement as a deterrent to intrusion
- 41 • waste characteristics, including migration behaviors of radionuclides and progeny
42

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

1 4.5 provide examples that should be considered by licensees in selecting a generic receptor
2 scenario to demonstrate the inadvertent intruder performance objective is met. Depending on
3 the characteristics of the disposal facility and its environment, licensees may need to or elect to
4 consider other site-specific receptor scenarios (e.g., industrial, urban, or recreational) or
5 consider additional exposure pathways (e.g., radon gas migration) to modify the generic
6 receptor scenarios.

7
8 Reviewers should assess a licensee's analysis of whether the generic receptor scenarios are
9 suitable representations of actual site conditions and disposal practices (e.g., the spatial
10 distribution of radionuclides). The reviewer should consult information provided to demonstrate
11 compliance with 10 CFR 61.12 to support the evaluation. NUREG-1199, Revision 2, "Standard
12 Format and Content of a License Application for a Low-Level Radioactive Waste Disposal
13 Facility," issued January 1991 (NRC, 1991a), provides guidance on information licensees
14 should submit to demonstrate compliance with 10 CFR 61.12.

15
16 NUREG-1200, Revision 3 (NRC, 1994), provides guidance for reviewers to evaluate the
17 sufficiency of the information submitted to demonstrate compliance with 10 CFR 61.12. In
18 general, the generic receptor scenarios are acceptable for demonstrating compliance if
19 licensees can demonstrate that the scenarios are suitable for the disposal facility and would
20 reasonably be expected to result in greater exposure to radiation from the waste than other
21 reasonably foreseeable receptor scenarios. The reviewer's evaluation should also assess the
22 licensee's justification for the evolution of site conditions over the time periods of interest (i.e.,
23 compliance period, protective assurance period, or performance period) and over what time the
24 conditions that may have supported the licensee's determination persist. For instance, if a
25 license applicant, in proposing a new facility, were to rely on a receptor scenario that is
26 consistent with activities that are anticipated around the site at closure, which could be many

Example 4.2

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

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

Example 4.3

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

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

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

Example 4.4

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

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

5 .

Example 4.5

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

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

1 Because of the uncertainties in projecting human behavior far into the future, there may be
2 limitless speculation on the types of activities an intruder may engage in, many possibly
3 unknown at this time. The activities represented by the generic receptor scenarios are
4 considered normal human activities (e.g., providing shelter, engaging in agriculture, and seeking
5 natural resources such as water) and avoid excessive speculation about future human activities.
6 The generic receptor scenarios also can be used to evaluate a nearly comprehensive set of
7 exposure pathways and are expected to be sufficient to assess the need for additional
8 measures to mitigate doses to inadvertent intruders. Licensees can use information on the
9 likelihood of natural processes to support receptor scenario development over the longer term.
10
11 For example, licensees can assess the effects of potential degradation of the capabilities of
12 intruder barriers (e.g., concrete degradation or erosion of cover materials) to justify when one of
13 the generic receptor scenarios can be initiated. However, speculating on future human
14 disruptive activities beyond a few hundred years should be avoided because there is no
15 scientifically credible basis to estimate the likelihood of a human disruptive activity so far into the
16 future. Reviewers should evaluate the licensee's scenario(s) for demonstrating the inadvertent
17 intruder performance objective is met for consistency with the types of activities associated with
18 the generic receptor scenarios described in this section or with the types of activities expected
19 in and around the disposal site at the time of closure for site-specific scenarios, which are
20 discussed in more detail in Section 4.3.1.2. Reviewers should also evaluate the technical basis
21 supporting the long-lived capabilities of intruder barriers and long-term evolution of the site
22 environmental conditions that may affect receptor scenarios. For example, a licensee should
23 appropriately consider long-term degradation processes such as corrosion or cement
24 degradation in evaluating the longevity of intruder barrier capabilities. Section 4.2.2 discusses
25 guidance for evaluating the longevity of intruder barrier capabilities. Section 2.2.3 discusses
26 considerations in evaluating whether a licensee has provided adequate model support to
27 provide confidence in the projection of long-term processes. Section 5.0 presents guidance on
28 long-term site stability (e.g., erosion).

1 **4.3.1.2 Site-Specific Intruder Receptor Scenarios**
2

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

26
27 The types of site-specific information that a licensee should use to justify selection of a receptor
28 scenario to demonstrate the inadvertent intruder performance objective is met are broadly
29 categorized as physical information and cultural information. Physical information includes the
30 location, climate, topography, geology, soil types, and water availability of the site, including
31 features of the disposal facility such as waste characteristics, disposal methods, and the use of
32 intruder barriers. Cultural information is essentially how the human population uses the land.
33 Physical properties of the site may change over time, particularly long time periods; however,
34 the change is expected to be slow compared to changes in the cultural use of the land.
35 Because of the uncertainty in estimating future human disruptive activities, cultural use of the
36 land is anticipated to be very uncertain over long time periods. Therefore, licensees should not
37 rely on cultural information as a basis for receptor scenario selection beyond a few hundred
38 years. Rather, licensees should limit consideration of cultural information to the operating
39 lifetime of the disposal facility.

40
41 The level of justification and analysis that should be provided by the licensee will depend on the
42 reasonableness of the physical characteristics the potentially foreseeable land uses, and the
43 length of time that the radiological hazard persists at the site. Licensees modifying generic
44 receptor scenarios or developing a site-specific intruder receptor scenario should consider the
45 performance of intruder barriers and the evolution of site characteristics over the duration of the
46 radiological hazard. Conversely, licensees modifying generic receptor scenarios or developing
47 site-specific intruder receptor scenarios should limit consideration of potential future uses of the
48 site and demographic information to the time of facility closure. Such considerations might
49 include characteristics of the disposed waste, disposal practices, degradation processes of

1 intruder barriers, estimates of the evolution of site characteristics, and, when appropriate, the
2 prevailing and possible future uses of the land, within the operational lifetime of the facility, that
3 could constrain use. Several potential intruder receptor scenarios may need to be evaluated to
4 determine the reasonably foreseeable receptor scenario resulting in the greatest exposure.
5 These scenarios could be based on different combinations of site-specific receptor scenarios
6 developed from radiological characteristics, disposal practices, evolution of physical
7 characteristics of the site, and expected land use.

8
9 Selection of site-specific receptor scenarios or the modification of generic exposure pathways
10 will typically require a technical basis that accounts for the longevity of the hazard. Licensees
11 should base justifications for modifying generic receptor pathways or developing unique site-
12 specific receptor scenarios on: (1) waste characteristics and disposal practices; (2) the nature
13 of the land and reasonable estimates based on physical and geologic characteristics; and (3)
14 societal uses of land based on past historical information, current uses, and what is reasonably
15 foreseeable in the near future (i.e., at the time of facility closure). The reviewer should evaluate
16 the justifications provided by the licensee for the selection of the receptor scenario(s) used to
17 demonstrate the inadvertent intruder performance objective and the screening of alternate
18 plausible receptor scenarios considering the following guidance related to the use of site-
19 specific information.

20 4.3.1.2.1 *Site-Specific Physical Information*

21
22 Physical information about the site includes information related to waste characteristics and
23 disposal practices as well as site physical characteristics. Site-specific physical information can
24 be used as a basis to modify the generic receptor scenarios and associated pathways. The
25 physical information should focus on key factors that would impact the likelihood of an intruder
26 who is engaging in normal activities (e.g., agriculture, dwelling construction, or other pursuits
27 such as resource exploration) or other reasonably foreseeable pursuits that are consistent with
28 activities in and around the site at the time of closure in which the person might be unknowingly
29 exposed to radiation from the waste.

30 4.3.1.2.1.1 Waste Characteristics and Disposal Practices

31
32 Licensees may consider both waste characteristics and disposal practices when developing an
33 appropriate receptor scenario to demonstrate the performance objective is met. This site-
34 specific information can affect the level of information needed to support the use of other
35 physical or cultural information. For example, the hazard from long-lived waste would require a
36 consideration of the evolution of site characteristics, such as climate, for a longer period than for
37 shorter-lived waste. Reviewers should consider the effects of this information on selection of an
38 appropriate receptor scenario.

39
40 A key waste characteristic is the longevity of the hazard from the disposed waste. The longevity
41 of the hazard should be considered as a factor when using other site-specific information to
42 develop receptor scenarios. For example, if a facility accepts only shorter-lived waste (e.g.,
43 waste containing only radionuclides with half-lives on the order of the radionuclides listed in
44 Table 2 in 10 CFR 61.55), then the consideration of the potential evolution of the physical
45 characteristics of the site can be limited to a shorter time period commensurate with the time it
46 takes for the shorter-lived waste to decay and result in an acceptable exposure to the
47 inadvertent intruder. For long-lived waste, consideration of land use information to justify the

1 selection of less conservative receptor scenarios may not be appropriate given the uncertainty
2 in estimating future human behavior. The use of land use information is discussed further in
3 Section 4.3.1.2.2 below.

4
5 Another important consideration is the use of disposal practices such as the presence of
6 intruder barriers (e.g., a wasteform designed to be recognizable for long time periods or the
7 depth of waste emplacement intended to limit direct contact with the waste). Intruder barriers
8 that are expected to be recognizable over a given timeframe may prevent inadvertent intrusion
9 or limit potential receptor scenarios over that time period. Licensees should provide an
10 adequate technical basis for the time period over which a barrier's capabilities would limit direct
11 contact with the waste or limit an inadvertent intruder's radiological exposure. Licensees are
12 expected to provide a technical basis to support the use of intruder barriers that are expected to
13 be effective for more than a few hundred years. The analysis should evaluate whether the
14 barrier precludes or mitigates intruder exposures. The technical basis should also consider the
15 evolution of the physical conditions to which the intruder barriers would be exposed over the
16 duration of the hazard.

17
18 For example, a licensee may rely on depth of disposal to limit the consideration of an intruder-
19 construction type of receptor scenario (see Example 4.6). In this example, the licensee's
20 technical basis for exclusion of an intruder-construction scenario should include an assessment
21 of the effects of erosion and other geomorphologic processes at the site to understand whether
22 the depth will be sufficient over the duration of the hazard of the disposed waste. Reviewers
23 should evaluate the adequacy of the technical basis for intruder barrier capability using the
24 guidance in Section 4.2.

Example 4.6

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

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

1 4.3.1.2.1.2 Characteristics of the Disposal Site
2

3 Licensees may consider the physical characteristics of their disposal site (e.g., the presence of
4 natural resources such as water and its quality and quantity, soil conditions, topography, and
5 climate) in justifying an appropriate receptor scenario to demonstrate the inadvertent intruder
6 performance objective is met. The consideration of physical characteristics often results in
7 modifications of receptor scenarios rather than complete elimination of the scenario type. For
8 example, farming may not be supported because of poor soil quality (i.e., not economically
9 practical), but residential gardening may still be reasonable. The justification should also
10 include an assessment of the physical characteristics over the period of time a significant
11 hazard from the disposed waste persists (see Example 4.7). Reviewers should evaluate the
12 justification for modifying generic receptor scenarios or selecting site-specific receptor scenarios
13 based on a site's physical characteristics.
14

Example 4.7

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

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

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

15
16
17 The existence of natural resources may result in reasonably foreseeable exploratory activities at
18 the site, though it should be noted that 10 CFR 61.50(a)(4) requires that areas that have known
19 natural resources that, if exploited, would result in failure to meet the performance objectives of

1 10 CFR Part 61, Subpart C must be avoided during siting. Because of the uncertainty in
2 estimating future human activity, licensees do not need to speculate on a future society's
3 interest in known resources that are not economically viable in the vicinity of the site after
4 closure. When reviewing the technical basis involving the presence or absence of economically
5 viable resources at the site, reviewers should limit speculation about natural resources that may
6 be economically viable to future societies after closure. Rather, reviewers should focus on
7 natural resources for which exploration is currently being conducted in the region of the site (i.e.,
8 within an 80-kilometer (50-mile) radius of the site). Natural resources not currently being
9 extracted in the region of the site may still be considered if their presence is currently known to
10 exist in economically viable quantities in the immediate vicinity of the site.

11
12 Justification to limit receptor scenarios and exposure pathways for intruders based on
13 groundwater quality and quantity should be based on site conditions rather than local codes and
14 should be based on classification systems used by the EPA or the State, as appropriate.
15 Arguments involving depth to water table or well production capacity should have supporting
16 documentation from either the U.S. Geological Survey (USGS), an appropriate State agency, or
17 an independent consultant. Tables M.5-M.12 in NUREG-1757, Appendix M (NRC, 2006)
18 provides additional details on water quality standards.

19
20 Licensees using soil quality as a justification for modifying receptor scenarios should provide
21 supporting documentation from the U.S. Natural Resources Conservation Service, appropriate
22 State or local agency, or an independent consultant. Reviewers should carefully consider
23 whether the state of the soil would reasonably preclude all activities or only certain activities. In
24 most cases, soil quality can reasonably preclude activities such as crop production, but could
25 allow grazing or small gardens.

26
27 Licensees using topography as a justification for modifying receptor scenarios should provide
28 supporting documentation of the existing topography in the form of pictures, USGS or similar
29 topographic maps, hand-drawn maps, or a detailed description of how the topography would
30 limit activities. Licensees may need to conduct landform evolution modeling that might also
31 include expert elicitation to provide support for reasonably foreseeable landform changes to
32 local topography. See Section 5.0 for additional guidance for long-term landform evolution.

33
34 When reviewing justifications involving topography, the reviewer should limit speculation about
35 future topographical changes from offsite civil engineering projects, but not topographical
36 changes from the final closure design of the disposal facility itself. The reviewer should
37 evaluate the reasonableness of the inadvertent intruder performing activities on the current
38 topography; for example, a slope, and reasonable evolution of the site due to geomorphologic
39 processes (e.g., fluvial, eolian, tectonic, biological). Reviewers may wish to perform a site visit
40 to evaluate the current topography first hand and assess how the disposal design may impact
41 the current topography. For example, reviewers may wish to assess the effect of runoff from a
42 licensee's cover system on erosion of the site topography.

43 4.3.1.2.2 *Site-Specific Cultural Information*

44
45 Licensees may consider cultural information in justifying an appropriate receptor scenario or
46 scenarios to demonstrate the performance objective is met. Cultural information is essentially
47 how land is used by the human population and describes the types of normal activities an
48 inadvertent intruder might engage in on the site. Information on land use can be based on past,

1 current, or projected land uses. The shorter of either the anticipated operational lifetime or one
2 hundred years is a reasonable period of interest for future land use projections to provide the
3 basis for receptor scenarios, depending on the rate of change in the region, and the peak
4 exposure time. Note that the 100-year timeframe described here is only for estimating future
5 land uses to justify a receptor scenario; the licensee must evaluate doses that could occur over
6 the time periods specified in the regulations. However, because of the uncertainty in estimating
7 future human behavior, cultural information projected beyond the operational lifetime of the
8 disposal facility should not typically be used as justification for a receptor scenario. Instead
9 licensees may rely on suitable physical information and should refer to Section 4.3.1.2.1 for
10 guidance on its use in justifying a scenario to demonstrate that the inadvertent intruder
11 performance objective is met.

12
13 A licensee's assumptions about land use should focus on current practice in the region of
14 concern, which can be as large as an 80-kilometer (50-mile) radius. To narrow the focus of
15 current land practices, the licensee can use information on how land use has been changing in
16 the region and should give more weight to land use practices either close to the site or in similar
17 physical settings. Licensees should also evaluate land uses that occur in locations outside the
18 region of concern that share characteristics (temperature, precipitation, topography) expected
19 for the region of concern over the duration evaluated in a site-specific receptor scenario.
20 Consideration of environmental-analog regions may help identify whether present-day land uses
21 have been driven by past socio-economic development. Land uses primarily resulting from
22 socio-economic development are generally more uncertain over longer time periods than land
23 uses primarily resulting from physical conditions (e.g., climate).

24
25 Licensees should categorize potential land use as reasonably foreseeable, less likely but
26 plausible, or implausible. Any land uses that similar real-estate properties in the region currently
27 have, or may have in the near future (e.g., in approximately 100 years or the operational lifetime
28 of the disposal facility) should be characterized as reasonably foreseeable. Consideration
29 should be given to trends and area land use plans in determining the likelihood of potential land
30 use. Land uses that are plausible, generally because similar land either was used for this
31 purpose historically in the region of interest, or is used currently in regions with analogous
32 environmental characteristics, but that are counter to current trends or regional experience
33 should be characterized as less likely but plausible. Licensees should provide either a
34 quantitative analysis or qualitative argument discounting the need to analyze all scenarios
35 generated from the less likely but plausible land uses. If peak doses from the less likely but
36 plausible land uses are significant, the licensee should provide greater support that the receptor
37 scenario is unlikely to occur. Implausible land uses are those that, because of physical
38 limitations, could not occur. Because of the uncertainty in predicting human behavior in the
39 future, land use information should be consistent with normal activities or other activities that
40 typically occur in and around the site at the time of closure of the disposal facility.

41
42 Reviewers should evaluate the justification provided for the selection of reasonably foreseeable
43 scenarios. One goal of the review is to ensure that, if land uses other than the reasonably
44 foreseeable land use were to occur in the future, significant exposure would not result.
45 Reviewers may wish to involve State and local land use planning agencies in discussions if the
46 licensee has not already requested their involvement. Additional guidance on potential sources
47 of land use information is available in Appendix M.5 to NUREG-1757 (NRC, 2006).

4.3.2 Model Abstraction

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

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

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

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

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

1 Further, NUREG-1293 (NRC, 1991c) provides specific guidance on how to meet the
2 10 CFR Part 61 QA requirements. If site-specific models and codes are used, a justification of
3 the conceptual model should be provided. Reviewers should also review the source term
4 models, the transport models, the exposure models, and the overall dose models. Reviewers
5 should assess the QA/QC documentation and the level of conservatism of any alternate code
6 and model. Section I.5 of NUREG-1757 (NRC, 2006) provides guidance, in the context of
7 decommissioning activities, which is generally relevant to intruder assessments on the selection
8 of codes and models and approaches for NRC acceptance of the codes and models. Section
9 2.7.1.2 of this document provides additional information on quality assurance.

10
11 The following sections discuss guidance on developing specific model abstractions for intruder
12 assessment and general model development issues.

13 **4.3.2.1 Intruder Barriers**

14
15 The intent of an intruder barrier is to inhibit contact with waste and help ensure that an
16 inadvertent intruder's radiation exposure will be limited, which provides reasonable assurance
17 that the performance objectives can be met. A variety of intruder barriers may be employed at a
18 waste disposal facility depending on the nature of the waste, the facility design, and the site
19 characteristics. Intruder barriers may include a sufficient depth of cover over the waste or
20 engineered structures that provide protection to the inadvertent intruder (e.g., engineered
21 covers, concrete vaults, engineered wasteforms, or waste containers). Each intruder barrier will
22 have a time period over which it will perform its intended functions, which should be justified by
23 the licensee. Additional guidance on justifying intruder barrier capabilities is available in Section
24 4.2.

25
26 The objective of intruder barrier model abstraction is to establish model representations of the
27 intruder barriers that are reasonably consistent with their intended capabilities and their
28 expected behavior with time. A primary outcome of the intruder barrier model abstraction is an
29 estimate of the time after disposal when intrusion could occur. This output is affected by the
30 particular intruder receptor scenario, the design of the intruder barrier system, and the impact of
31 natural processes on the longevity of the intruder barriers' capabilities. Reviewers should apply
32 the general guidance in Section 2.7.2 when evaluating the abstraction of intruder barriers in the
33 intruder assessment. Reviewers should consider the degree to which the licensee relies on the
34 capabilities of the intruder barriers to demonstrate the performance objective is met. For
35 intruder assessments for which licensees have demonstrated that intruder barriers have a minor
36 impact on protection of the intruder, a simplified review should be sufficient.

37
38 The nature of the activities in which an inadvertent intruder might engage will affect the time at
39 which an intruder might unknowingly be exposed to radiation from the waste. Licensees should
40 assess the capability of the intruder barrier system to preclude contact with the waste or limit
41 radiological exposures. For example, construction activities could be limited to the discovery
42 receptor scenario as long as the wasteform remains stable, and is, therefore, expected to be
43 distinguishable from soil. Licensees should provide a technical basis for the ability of the
44 intruder barrier to delay the time of initiation for intruder activities. The level of detail in the
45 technical basis should be commensurate with the delay time afforded by the capabilities of the
46 intruder barrier. Barriers providing substantial delay time would require a more robust technical
47 basis. The technical basis should consider insights gained from scenario analysis and
48 beneficial as well as deleterious natural processes that may affect the capability of the barrier to

1 preclude the intruder activities. Reviewers should focus on those barriers that provide
2 substantial delay time to the onset of intruder activities; activities that otherwise would result in
3 direct contact with the waste or other radiological exposures.

4
5 In developing intruder barrier models, the licensee should present information on spatial
6 relationships among the physical components (e.g., the layout and physical dimensions of a
7 vault or cover system) and the physical distribution of various types of materials that are used in
8 the intruder barriers. The intruder assessment should include features of the intruder barriers
9 that are most important to demonstrating the performance objective is met. Licensees should
10 ensure that the models for intruder barriers are integrated with related model abstractions. For
11 example, the conditions and assumptions used in the degradation of intruder barriers should be
12 consistent with those used for other model abstractions (e.g., climate and infiltration).

13
14 Reviewers should examine the identified physical components that are important to
15 demonstrating the performance objective is met and evaluate whether their representation in the
16 intruder assessment modeling is consistent with their description, the technical basis supporting
17 their capabilities, and other model abstractions. The review should assess whether the
18 descriptions are adequate to detail the important design features, capabilities, and properties of
19 the barriers (e.g., thickness, porosity, or saturation of a cover layer designed to limit gaseous
20 fluxes to the surface). The modeling of intruder barriers by licensees should reflect the level of
21 quality that is expected to be achieved in the implementation of the design. Reviewers should
22 assess whether the level of quality being proposed can be attained, that it is supported by an
23 acceptable quality assurance program, and that it is adequately represented in the abstraction.

24
25 Licensees should evaluate processes that may limit the effectiveness of the intruder barriers.
26 Barriers may degrade from internal processes (e.g., interaction between incompatible materials,
27 interaction with the waste) or external processes (e.g., interaction with biota, erosion, leaching
28 by infiltrating water, and processes such as seismically induced cracking). Analysis of a barrier
29 system should be performed in an integrated manner because of potential synergisms between
30 degradation mechanisms. If the analysis is performed assuming that the degradation
31 mechanisms are independent, the reviewer should evaluate the information to determine
32 whether an adequate basis has been provided for the analysis approach (e.g., assuming that
33 the degradation mechanisms can be evaluated as independent). This may include
34 demonstrating that the degradation analysis was reasonably conservative or that uncertainty
35 was adequately characterized and propagated in the model. Reviewers should also verify that
36 the models for degradation of intruder barriers are consistent with environmental parameters,
37 material properties, and assumptions implemented in the performance assessment.

38
39 The intruder assessment should account for relevant materials and conditions that could affect
40 the ability of an inadvertent intruder to contact the waste over time. Licensees should consider
41 interactions of the components and materials of the intruder barriers. Factors that may need to
42 be considered include (1) compatibility among materials that may come into contact with each
43 other, (2) the manner in which construction may affect system behavior (e.g., construction joints,
44 changes in geometry, penetrations), (3) the effect that failure of a design feature or some
45 portion of an intruder barrier would have on the overall ability of the intruder barrier system to
46 limit contact with the waste, and (4) how the degradation of material properties affects barrier
47 performance over time.

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

Example 4.8

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

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

15
16 Licensees should provide information to support the model estimates of intruder barrier
17 performance. Section 2.2.3 of this document provides guidance on model support. Model
18 support can include laboratory experiments, field measurements, previous experience with
19 similar systems, process modeling of barrier performance (e.g., detailed models of landform
20 evolution to estimate cover erosion), natural or industrial analogs, independent peer review
21 (NRC, 1988a), or additional sources of relevant information. Reviewers should examine the
22 evidence supporting the modeling to confirm that the information is based on similar
23 environmental parameters, material factors, assumptions, and approximations shown to be
24 appropriately analogous and that the models are not likely to underestimate actual degradation
25 and failure of intruder barriers. Reviewers should also examine the procedures that the licensee

1 used to construct and test its mathematical and numerical models. Section 4.2.1 provides
2 guidance on a risk-informed approach to model support for engineered barrier capabilities.
3

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

8 **4.3.2.2 Source Term**

9

10 The objective of the source term abstraction in an intruder assessment is to estimate the
11 radionuclide concentrations in the environment (i.e., the biosphere) accessible to the inadvertent
12 intruder. The modeling of the source term can be one of the most important determinants of the
13 estimated exposures to an inadvertent intruder. Typically, source term modeling includes the
14 inventory of radionuclides, physical and chemical characteristics, and other properties used to
15 estimate release rates.
16

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

27 **4.3.2.2.1 Inventory**

28

29 Assumptions about the characteristics of the radionuclide inventory can have a significant effect
30 on the determination and selection of modeling approaches appropriate for representing the
31 source term. Radionuclide inventories need to be addressed on a facility-specific basis. The
32 anticipated distribution of specific radionuclides in the disposal facility inventory should be
33 estimated by waste class (A, B, and C), waste type, wasteform, waste stream, and waste
34 container type, as appropriate. This information provides a basis for selecting an approach for
35 source term modeling. The necessary level of detail in this information will vary with the
36 modeling approaches under consideration. For example, the source term model for direct
37 contact receptor scenarios in which a discrete volume of waste is exhumed may be more
38 stylized than for other scenarios involving release from the disposal units.
39

40 Licensees should provide a description of the radionuclide inventory in the disposal facility. All
41 radionuclides should be described by volume, concentration, and location within the disposal
42 system. The radionuclide inventory should be consistent with the resulting waste acceptance
43 criteria as well as the inventory used in the performance assessment to assess whether the
44 requirements of 10 CFR 61.41 are demonstrated. However, in some cases, licensees may use
45 conservative estimates of inventory in the intruder assessment and more realistic estimates in
46 the performance assessments.
47

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

4
5 Licensees may use a screening approach to determine which radionuclides in the facility
6 inventory need to be considered further in the intruder assessment. Licensees may:

- 7
8 (1) Eliminate radionuclides with half-lives less than 5 years that are not present in
9 significant activity levels and do not have long-lived daughter products.
- 10
11 (2) Perform an intruder dose calculation using the generic receptor scenarios discussed in
12 Section 4.3.1.1 assuming that the intruder inadvertently intrudes into the spatially
13 averaged peak waste concentration and that all intruder barriers are completely
14 ineffective in inhibiting contact with the waste. All radionuclides are assumed to be
15 available for all relevant exposure pathways of each generic receptor scenario.
16 Radionuclides with an estimated peak dose in each of the receptor scenarios that is less
17 than 10 percent of the performance objective can be eliminated from further
18 consideration provided that the sum of their doses is accounted for in demonstrating the
19 performance objective is met. If a radionuclide has an estimated peak dose greater
20 than or equal to 10 percent of the performance objective in any of the generic receptor
21 scenarios, the radionuclide should be retained for the final intruder assessment.
22 Computer models such as RESRAD (Yu et al., 2001) may be useful to conduct this type
23 of screening analysis. To ensure that important radionuclides are not inadvertently
24 screened out of the assessment, it is important to confirm that the dominant pathways
25 (i.e., those contributing most to estimated dose) in the screening calculation are
26 consistent with those in the final intruder assessment.

27
28 Reviewers should examine the description of the screening assessment to ensure that the
29 licensee used reasonably conservative parameters and appropriately screened the
30 radionuclides.

31
32 For intruder receptor scenarios in which direct contact with the waste occurs, source term
33 modeling can be as simple as distributing a concentration of radionuclides in the biosphere for
34 exposure modeling. For receptor scenarios with indirect releases from the disposal cells, such
35 as through advective-diffusive release mechanisms, licensees may develop source term
36 abstractions similar to those in the performance assessment (see Section 3.1). Licensees may
37 also use estimated concentrations from the performance assessment at an appropriate location
38 and point in time to assess exposures to the inadvertent intruder in the biosphere.

39
40 Reviewers should verify that licensees using radionuclide concentrations from the performance
41 assessment have not overestimated releases in the performance assessment to conservatively
42 estimate doses to the general public, resulting in a potential underestimation of radionuclide
43 concentrations in the intruder assessment.

44
45 Licensees should also consider the radioactive decay before the time of intrusion or may
46 conservatively assume no decay. In either case, however, licensees should consider the
47 impacts of significant progeny on the intruder. Radioactive decay can result in significant
48 ingrowth of progeny at future times. For example, doses from depleted uranium may increase
49 for more than one million years due to ingrowth of shorter-lived and more highly mobile decay

1 products. Given that the regulations specify that 100 years is the maximum duration over which
2 active institutional controls can be relied upon, radioactive decay is expected to be more
3 important in direct contact receptor scenarios for shorter-lived radionuclides such as cesium-
4 137. Reviewers should verify that radioactive decay is appropriately accounted for in the
5 source-term modeling.
6

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

11 4.3.2.2.2 *Radionuclide Concentrations for Direct Contact Scenarios*

12

13 To develop the source term abstraction, licensees should estimate the concentration of
14 radionuclides in the facility at times after which the direct contact scenarios would be expected
15 to occur. Estimating the time after which a direct contact scenario could occur is related to the
16 assumed institutional control period (see Section 4.4), intruder activities envisioned in the
17 receptor scenario, and the capabilities of intruder barriers to preclude intrusion. Section 4.3.2.1
18 provides guidance on the capabilities of intruder barriers to preclude intrusion.
19

20 Licensees should consider the following elements when generating concentrations of
21 radionuclides for the intruder dose assessment:
22

- 23 • Licensees are permitted to account for dilution of the waste following disposal due to
24 mixing with uncontaminated materials in the disposal cells.
- 25 • The amount of mixing should account for methods of waste emplacement such as
26 disposal depth.
- 27 • The justification for the amount of mixing may rely on site characteristics.
- 28 • The justification may include reasonable assumptions about the intruder activities.
29

30 Licensees are permitted to account for dilution of the waste following disposal due to mixing with
31 uncontaminated materials in the disposal cells. Licensees should provide a technical basis for
32 dilution of the waste mixed with uncontaminated materials. Mixing should be consistent with the
33 design of the facility, waste emplacement, site characteristics and assumptions about intruder
34 activities for a given scenario. The design of the facility may incorporate uncontaminated
35 materials within the disposal cells that would tend to reduce radionuclide concentrations found
36 in the waste. Design features may include intruder barriers and stabilization materials such as
37 backfill or grout. For example, waste may be emplaced beneath an engineered cover with
38 uncontaminated backfill material to help maintain the stability of the disposal cells. The
39 uncontaminated cover and backfill would likely reduce radionuclide concentrations found in the
40 waste when mixed during excavation, as considered in an intruder-construction scenario.
41

42 The amount of mixing should account for methods of waste emplacement. For example, the
43 intruder-construction scenario typically only excavates a depth necessary to construct a
44 dwelling. Waste and backfill placed beneath this depth should not be considered in the mixing
45 assessment. The justification for the amount of mixing may rely on site characteristics. For
46 example, the thickness of uncontaminated soil between the bottom of the disposal cells and the

1 underlying aquifer or resource may also be considered in estimating dilution for an
2 intruder-driller scenario. To justify mixing based on deeper aquifers or resources, licensees
3 should explain why mixing with the uncontaminated soils between the bottom of the disposal
4 cells and the depth of the deeper aquifers or resources would be more appropriate than a
5 smaller mixing volume associated with shallower aquifers or resources. Licensees should limit
6 this mixing volume to the shallowest aquifer or resource that would be reasonable to access for
7 water or the natural resource. Licensees should also consider the impact of variability in the
8 mixing volume associated with the use of shallower aquifers or resources if it is plausible that an
9 inadvertent intruder might access the shallower aquifer or resources.

10
11 In the absence of knowledge that the site is a disposal facility, it may be considered reasonable
12 to assume that an intruder will excavate at random locations. In this case, the excavation could
13 exhume material that was contained within multiple waste packages or disposal cells.
14 Therefore, the waste concentration for estimating intruder impacts from excavation can be
15 averaged over the area of the site where waste is disposed, including uncontaminated regions
16 within the disposal cells (e.g., backfill). Portions of the site beyond the disposal cell footprints,
17 such as administrative areas or the buffer zone, should not be included in the areal-average of
18 the waste concentrations. If the excavation area is larger than the disposal cell area, dilution
19 with uncontaminated soil surrounding the disposal cell may be considered.

20
21 For intruder-driller scenarios, the waste concentrations may be based on the average
22 concentration in the waste containers (for containerized waste) or the average concentration of
23 the waste for bulk waste. Uncontaminated material above and below the waste may be credited
24 in the intruder-driller waste concentration calculations. However, uncontaminated material
25 within the disposal cell (e.g., backfill) should not be credited because the intruder driller disturbs
26 a small, discrete area. Operational limits, such as waste emplacement strategies, may be
27 necessary to limit the impact from wastes with significant heterogeneity that is near class limits.

28
29 Licensees should provide a basis to justify the suitability of the random access assumption. For
30 example, at an aboveground disposal facility characterized by mounded disposal cells that
31 create a “ridge and valley” topography in which the disposal mounds are expansive with gentle
32 terrain and are separated by steep and narrow “valleys” that are uncontaminated, licensees can
33 argue that the excavation of a dwelling foundation would preferentially occur on the expansive
34 “ridges” rather than in the steeper, narrower “valleys”. In this case, random access may not be
35 an appropriate assumption for an intruder-construction scenario.

36
37 Reviewers should evaluate the reasonableness of the technical basis supporting the dilution of
38 waste concentrations. The review should consider the facility design, waste emplacement, site
39 characteristics, and scenario assumptions. Generally, the more mixing that is assumed, the
40 more robust the technical basis should be to support the dilution factor.

41
42 Radionuclides that are released offsite through natural processes before intrusion are generally
43 not available to be exhumed by an inadvertent intruder. Licensees may consider radionuclide
44 migration before the commencement of the intruder activities. Licensees may use information
45 from the performance assessment to estimate radionuclide releases. However, licensees
46 should exercise caution with this approach if the performance assessment overestimates
47 releases to conservatively assess exposures to the general public. This may result in an
48 underestimation of waste concentrations remaining for the intruder to access.

49

1 Reviewers should assess the consistency between radionuclide releases estimated in the
2 intruder assessment and in the performance assessment. Reviewers should ensure that
3 pessimistic modeling biases and assumptions in the performance assessment do not result in
4 overly optimistic biases in the intruder assessment.
5

6 The spatial extent over which exhumed waste is deposited at the surface on site will depend on
7 the activities assumed to occur in the intrusion receptor scenario (e.g., drill cuttings
8 management practices) and physical arguments about the exhumed volumes (i.e., how widely
9 can a volume of exhumed waste physically be spread?). The area over which exhumed
10 material is spread may be an important parameter because it can limit certain exposure
11 pathways. For example, too small an area may make certain agricultural pathways unviable,
12 while too large an area may unreasonably dilute the concentration of the waste exhumed. For
13 the spatial distribution of the exhumed radionuclides, licensees should use reasonable physical
14 assumptions consistent with the scenario assumptions. For example, a small volume of drill
15 cuttings is not likely to be spread over a large area of the site.
16

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

20 4.3.2.2.3 *Radionuclide Concentrations for Transport Scenarios*

21
22 Reviewers should assess the adequacy of the radionuclide release and transport models in the
23 intruder assessment consistent with the guidance in Sections 3.2 and 3.3 of this document.
24 Radionuclide concentrations for intruder transport scenarios typically involve an estimation of
25 environmental concentrations after release and transport through the disposal site environment.
26 The release and transport are typically controlled by natural processes (e.g., degradation,
27 sorption). The performance assessment for demonstrating that the requirements of
28 10 CFR 61.41 are met also estimates radionuclide releases from the source term of a disposal
29 facility that are controlled by natural processes.
30

31 There are a few exceptions to the similarity between a performance assessment and an intruder
32 assessment. First, access points for the intruder to the contaminated environmental media
33 should all be on site. Offsite exposures are assessed in the performance assessment for
34 demonstrating that the performance objective for protection of the general population is met.
35 Second, intruder receptor scenarios are typically independent. For example, the intruder who
36 contacts the waste during construction of a dwelling may not be the same individual who lives in
37 the dwelling. The radiological exposures from these receptor scenarios are generally mutually-
38 exclusive and not additive. However, there may be some cases in which it would be appropriate
39 for receptor scenarios to be dependent. For example, it would be reasonable to assume that a
40 well is installed to supply water to a dwelling that is constructed on the site and that the intruder
41 residing in the dwelling is also exposed to contaminated ground water from the well. When
42 dependent receptor scenarios are used and one is a direct contact scenario and the other is a
43 migration scenario, the licensee may provide a basis for including the removal of some of the
44 waste from the disposal cell at the time of the intrusion event in order to calculate releases from
45 the buried waste for the transport scenario. Licensees should also assess the transport of
46 waste that was accessed by the intruder (i.e., the transport of radionuclides from waste that was
47 excavated by the intruder).
48

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

8 **4.3.2.3** *Transport*

9
10 Radionuclides directly contacted by an inadvertent intruder or released from disposal units may
11 be transported in the general environment by groundwater, surface water, air, and biota (e.g.,
12 rodents). Model abstraction for transport processes in an intruder assessment is generally
13 similar to model abstraction for transport processes in a performance assessment. Therefore,
14 the guidance in Section 3.2 of this document is generally applicable to an intruder assessment.
15 One notable exception is that an intruder assessment is focused on exposures on site.
16 Therefore, model abstraction of transport processes should be focused on onsite transport
17 processes for an inadvertent intruder assessment. This may include gaseous diffusion of
18 radionuclides from the disposal unit through the overburden to an intruder at the surface or
19 leaching from the disposal units and transport via groundwater to the intruder well at the site
20 boundary. Radionuclides released from the disposal units that are transported beyond the site
21 boundary (i.e., off site) are generally evaluated in a performance assessment for members of
22 the public and would not need to be considered in an inadvertent intruder assessment.

23 **4.3.2.4** *Dose*

24
25 The objective of the dose modeling in an inadvertent intruder assessment is to provide
26 estimates of potential doses to an inadvertent intruder, in terms of the average member of the
27 critical group, from direct contact with disposed waste or onsite releases from an LLW disposal
28 facility after the period of active institutional controls. In this role, dose modeling integrates the
29 information from the various modeling areas. In general, dose modeling in an intruder
30 assessment is similar to dose modeling in a performance assessment. Dose modeling consists
31 of converting radionuclide concentrations in environmental media to dose through various
32 exposure pathways. Guidance on development of receptor scenarios is discussed in Section
33 2.2.4.2 of this document, and guidance on the dosimetry parameters is discussed in Section
34 2.2.4.3. Additional guidance applicable to modeling of exposure pathways in intruder
35 assessment are discussed in the following sections.

36
37 The exposure pathway models link the radiological source, transport of radionuclides within
38 environmental media, receptor location, and behaviors of the receptor that lead to its exposure
39 to radionuclides through direct exposure, inhalation, and ingestion of contaminated water, soil,
40 plants, and animal products.

41
42 Reviewers should evaluate the conceptual models that describe the human behaviors that lead
43 or control the amount of receptor exposure. Therefore, the occupational, behavioral, and
44 metabolic parameters describing these models should be reviewed and compared with the
45 receptor scenarios and associated parameters.

46

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

11
12 A brief summary of the NRC-recommended process for exposure pathway analysis follows:
13

- 14 (1) Compile a list of exposure pathways applicable to any site containing radionuclides.
15 There are a number of existing sources of information that can be used;
16 e.g., NUREG/CR-5512, Volume 1 (NRC, 1992); NUREG-1757, Volume 2 (NRC, 2006);
17 NUREG/CR-5453, "Background Information for the Development of a Low-Level Waste
18 Performance Assessment Methodology," Volumes 1 and 2 (NRC, 1989b; NRC, 1989c);
19 and the International list of Features, Events, and Processes (SSI, 1996).
- 20 (2) Categorize the general sources of radioactivity at the site (e.g., mixed in sediment or
21 soil, groundwater).
- 22 (3) Screen out pathways for each source of radioactivity that do not apply to the site.
- 23 (4) Identify the physical processes pertinent to the remaining pathways for the site.
- 24 (5) Separate the list of exposure pathways into unique pairs of exposure media (e.g., source
25 to groundwater). Determine the physical processes that are relevant for each exposure
26 media pair and combine the processes with the pathway links.
- 27 (6) Reassemble exposure pathways for each source type, using the exposure media pairs
28 as building blocks, thus associating all of the physical processes identified for the
29 individual pairs with the complete pathway.
30

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

40 **4.4 Institutional Controls**

41
42 As required in 10 CFR 61.23(g), a licensee must provide reasonable assurance that institutional
43 controls will be provided for enough time to protect the general population from releases per
44 10 CFR 61.41, to protect individual inadvertent intruders per 10 CFR 61.42, to assure that
45 radiation standards in Part 20 will be met per 10 CFR 61.43, and to provide long-term stability of

1 the disposed waste and disposal site per 10 CFR 61.44. In the context of inadvertent intrusion,
2 institutional controls are used to limit intruder access to, and/or use of the site for a period of
3 time following transfer of the disposal site to the owner and cannot be relied on for more than
4 100 years under 10 CFR 61.59. An institutional control program includes legal mechanisms
5 (e.g., land use restrictions), environmental monitoring, periodic surveillance, minor custodial
6 care, or other requirements as determined by the Commission, as well as the administration of
7 funds to cover the costs for these activities. For the purposes of the intruder assessment, the
8 institutional control period is separated into an “active” and “passive” period. During the active
9 period, which cannot be relied on for more than 100 years, monitoring, surveillance, and
10 custodial activities may be assumed to be carried out by the site owner. During this period,
11 licensees may assume that the institutional controls are durable and will preclude inadvertent
12 intrusion from occurring at the disposal site. The passive period follows the active period, and
13 during this period it should be assumed that relatively few custodial activities are carried out.
14 Inadvertent intrusion is expected to be unlikely due to the passive-period legal mechanisms, but
15 is possible after 100 years, consistent with 10 CFR 61.59.

16
17
18

5.0 SITE STABILITY ANALYSES

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

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

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

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

Many of the early problems associated with LLW disposal arose from site stability issues primarily associated with water (NRC, 2007b). To address these problems, a number of practical regulatory requirements, such as waste segregation requirements, were introduced to the regulations to obviate or limit future problems associated with waste stability (NRC, 1982a). Disposal of long-lived waste can increase the disposal challenge associated with ensuring waste stability, relative to short-lived LLW. For long-lived waste, it may be difficult to demonstrate the performance of the engineered features used to ensure waste stability, because the service life of those features is relatively short compared to the time those wastes remain hazardous. Site stability, in addition to the physical and chemical stability of the waste

1 itself, can affect the performance of the waste disposal facility. Instability can be initiated by
2 internal or external phenomena. NUREG-1200 provides details about site stability focused on
3 waste stability, erosion protection, and geotechnical issues (slope stability, settlement,
4 subsidence) (NRC, 1994). The guidance in this document is not a substitute for the information
5 found in NUREG-1200; it can be used to supplement NUREG-1200, in particular for the site
6 stability analyses associated with long-lived LLW. Within this guidance document, the term “site
7 stability” is used to refer to the overall stability of the LLW disposal system, which includes
8 stability of the waste, disposal site, and disposal facility and surrounding environment, as
9 applicable.

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

28
29 Stability and uncertainty are interrelated topics. Site stability analyses should be developed and
30 evaluated in a risk-informed manner. Section 61.44 requires that site stability must be
31 demonstrated for the compliance and protective assurance periods. As timeframes increase,
32 the uncertainty associated with site stability increases. In addition, the scope and diversity of
33 phenomena that may impact the stability of the disposal site increases. As previously noted,
34 stability is to be applied in the context of meeting the performance objectives for 10 CFR 61.41
35 and 10 CFR 61.42. However, site stability is an independent performance objective (10 CFR
36 61.44). Uncertainty associated with high instability may limit the ability of a licensee to
37 demonstrate that 10 CFR 61.41 and 10 CFR 61.42 can be met. Inventory limits may be used to
38 mitigate the uncertainties associated with potential instability, or to prohibit disposal of waste
39 that remains hazardous when the instability is projected to occur.

40
41 Section 61.50 of 10 CFR Part 61 provides the disposal site suitability requirements used in the
42 site selection and evaluation process. Licensees can use site selection to eliminate or greatly
43 reduce the number of disruptive processes and events that may need to be considered in the
44 site stability analysis. For example, alluvial fans that form at the base of mountain ranges tend
45 to be particularly unstable landforms over the long-term (NRC, 1983b).

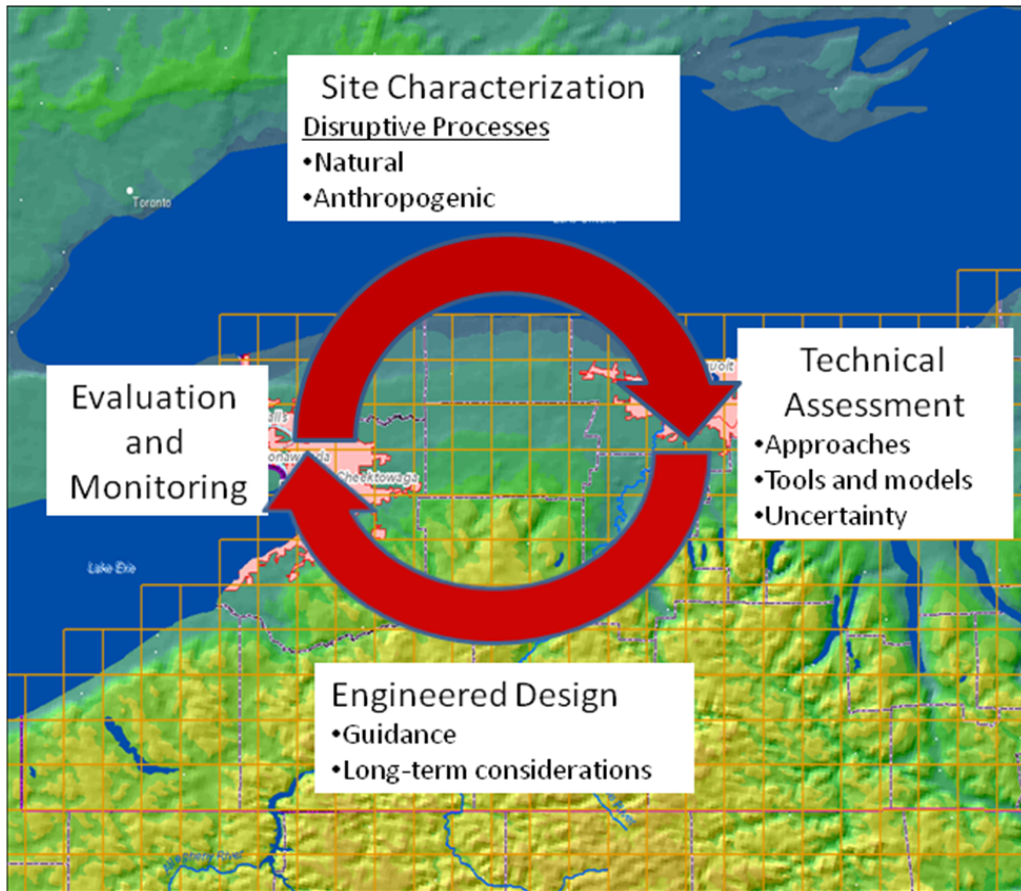


Figure 5-1 Main Elements of Site Stability Analysis

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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 site¹ 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

1 discharge to the surface), that they shall not significantly affect the ability of the disposal facility
2 to meet the Subpart C performance objectives of the regulations.
3

4 The other site suitability requirements in 10 CFR 61.50(a)(4) specify characteristics of the site
5 that should not be present such that they significantly affect the ability of the disposal site to
6 meet the performance objectives of Subpart C (e.g., population growth, tectonic processes).
7 The requirements in 10 CFR 61.50(a)(4) can exclude a potential disposal site location only if the
8 FEP in question (e.g., tectonic processes, see Section 2.0) may prevent the performance
9 objectives from being met, or if defensible modeling is precluded. For FEPs that result in severe
10 disruption, defensible modeling may be precluded, and licensees, in concert with their
11 regulators, may need to establish conservative inventory limits to mitigate the associated
12 uncertainties. Practical solutions, other than numerical modeling, to limiting the impact of
13 uncertainties associated with the disposal of long-lived waste may be necessary. Requirements
14 associated with specific FEPs associated with site stability are provided in 10 CFR 61.50,
15 including, but not limited to, the following:
16

- 17 • Areas must be avoided where tectonic processes such as faulting, folding, seismic
18 activity, or volcanism may occur with such frequency and extent to significantly affect the
19 ability of the disposal site to meet the performance objectives of Subpart C of this part,
20 or may preclude defensible modeling and prediction of long-term impacts.
21 [10 CFR 61.50(a)(4)(iii)]
22
- 23 • Areas must be avoided where surface geologic processes such as mass wasting,
24 erosion, slumping, land sliding, or weathering occur with such frequency and extent to
25 significantly affect the ability of the disposal site to meet the performance objectives of
26 Subpart C of this part, or may preclude defensible modeling and prediction of long-term
27 impacts. [10 CFR 61.50(a)(4)(iv)]
28

29 Site stability analyses should be tailored to the types of waste disposed. A facility designed for
30 what might be regarded as traditional LLW streams (i.e., short-lived waste and low
31 concentrations or quantities of long-lived waste) will have comparatively less complex site
32 stability analyses than a facility designed for large quantities of concentrated, long-lived waste.
33 For example, higher quality rock and more detailed testing and assessment of the durability of
34 rock used for erosion protection will be needed for long-lived waste (compared to short-lived
35 waste). Site stability analyses have three areas of focus: stability of the wastefrom, stability of
36 the engineered disposal facility, and geologic/geomorphic stability of the disposal site. For
37 disposal of traditional LLW, site stability analyses will likely focus on the former two areas. For
38 disposal of large quantities of long-lived waste, the focus will likely be on the latter two areas.
39 The areal extent of the site stability analyses will be strongly influenced by the type of waste to
40 be disposed. Stability of wastefroms, disposal units, engineered barriers (such as cover
41 systems), disposal site, disposal facility, and disposal system may all be within the scope of the
42 stability assessment.
43

44 The scope of the analyses needed for the site stability evaluation will be defined primarily by the
45 type of waste and secondarily by the disposal system. The type of waste (i.e., short-lived or
46 long-lived) will determine the timeframe appropriate for the site stability assessment, and
47 therefore, what types of FEPs a licensee should evaluate. Waste disposal systems are
48 generally reliant on passive features of the site geology/hydrology to limit long-term releases of
49 radioactivity. To limit short-term releases, waste disposal systems may be strongly reliant on

1 the performance of engineered systems. Passive systems, in general, will be more resistant to
2 failure from unlikely natural events than active systems. Figure 5-2 provides an integrated view
3 of the NRC staff's perspective on the temporal and spatial scales as well as the relative
4 influence of various processes on site stability for LLW disposal.

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

11
12 Figure 5-2 is a generalization; however, the relative importance of a particular process at a
13 specific site may differ from the conceptualization shown in the figure primarily as a result of
14 location of the site. For instance, based on historical data, glaciation at a southern state would
15 be expected to be of lower relative importance compared to glaciation at a northern state.
16 Individual processes may also be dynamic such that the relative importance is not constant over
17 time. The relative importance of climate could change based on the magnitude of effects of
18 anthropogenic processes on climate change. With these types of caveats, the general
19 expectation of the relative influences of various processes on site stability is:

- 20 1) In the near term (left hand side of the figure), erosion is expected to be the dominant
21 process impacting stability. Secondary processes are biologic and climate. Igneous and
22 tectonic phenomena are expected to be insignificant for a properly selected site.
23 Glaciation is not anticipated in the near term.
- 24 2) In the medium term (middle of the figure), erosion is still of primary importance, but
25 changes to climate which can impact erosion or result in glaciation at some sites
26 become more significant.
- 27 3) On the long term (right hand side of the figure), most processes are expected to be
28 important to evaluate in the stability assessment. As time increases, the likelihood of a
29 large, low frequency seismic or volcanic event occurring increases.
- 30 4) The overall significance of various processes on site stability increases as time
31 progresses. Over long timeframes, there is a higher overall likelihood that site stability
32 will be affected by one or more of the processes.

33
34 A variety of resources are available to facilitate the development or review of site stability
35 analyses. This section attempts to consolidate and summarize some of these resources but
36 does not attempt to replicate them. The reader of this document should consult the original
37 documents for more detailed information, as needed.

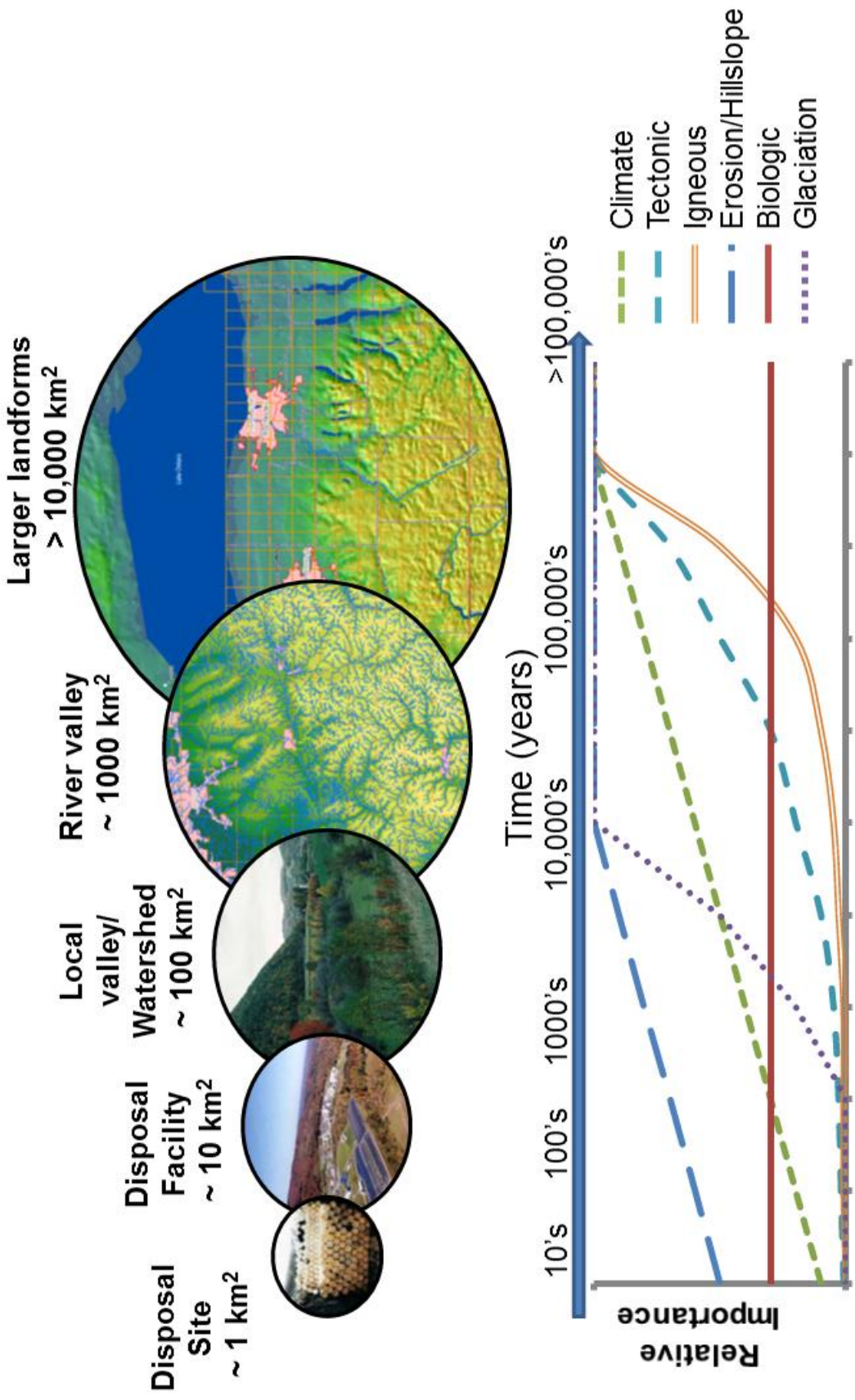


Figure 5-2 Spatial and Temporal Scales and NRC Staff Perspective on the Relative Importance of Various Geomorphological Processes Relevant to LLW Disposal.

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

5.1 Disruptive Processes and Events

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

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

- Which disruptive phenomena need to be evaluated?
 - What screening process will be used?
 - What criteria will be used for screening?
- How may the phenomena influence each other (i.e., are they correlated, dependent, independent)?
- Can the frequency and consequences of the events or processes impact the demonstration of compliance with the performance objectives of 10 CFR Part 61, Subpart C?

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

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

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

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

9
10 Licensees should use a screening process to determine which processes and events need to be
11 considered in the stability analysis. Processes and events can be screened out of the
12 assessment based on probability, consequence, risk-based criteria (i.e., the combination of
13 probability and consequence), or regulation (see Section 2.5.3.1.2). Screening based on
14 probability typically establishes a cutoff frequency below which disruptive events are not
15 considered further. This cutoff frequency is expected to be higher for LLW analyses compared
16 to HLW analyses because the consequences of disruptive events are likely to be less severe for
17 less-concentrated waste than for HLW. Screening of disruptive processes and events based on
18 consequence or risk should consider the integrated effect of the process or event. For example,
19 the growth of trees and eventual tree fall on a cover may not significantly impact the stability of
20 the cover from the event itself, but it may create a depression to initiate future gullying. In many
21 cases, there is limited experience, and therefore, limited understanding of potential combined
22 phenomena. Although the uncertainty associated with combined phenomena cannot be
23 reduced, the use of multiple independent peer reviewers with diverse backgrounds can reduce
24 the likelihood of omitting important combined effects.

25 **5.1.1 Natural Processes**

26
27 The near-surface environment is continually evolving, influenced by processes as well as by
28 discrete events. The processes and events may interact, compounding or reducing the effects
29 observed from the individual phenomena. The systems are dynamic and may include positive
30 or negative feedback effects. The phenomena most likely to impact the stability of a disposal
31 facility, and therefore, the demonstration of compliance with the performance objectives of
32 10 CFR Part 61, Subpart C, will be specific to the particular site and design. This section covers
33 different types of natural processes that can impact disposal facility stability. Geomorphic (e.g.,
34 mass wasting, erosion, slumping, land sliding, or weathering), tectonic (e.g., faulting, folding,
35 seismic activity, or volcanism), biologic (e.g., animal or plant intrusion), or other processes and
36 events (e.g., flood, fire, or extreme weather) may impact the future stability of waste disposal
37 facilities. Processes and events may impact stability either directly (e.g., a large flood) or
38 indirectly (e.g., a fire that disturbs vegetation, leading to increased erosion). In general,
39 geomorphic processes will be the most likely stressors of long-term performance for most
40 facilities.

41
42 Geomorphology is multidisciplinary, combining aspects of hydrology, climatology, ecology, and
43 geology. Landform evolution is the sequence of processes and events that shape a given
44 landscape. Landforms are built through tectonic, volcanic, and sedimentation processes and
45 reduced through such processes as erosion and mass wasting. Evolution of landforms is
46 associated with the balance between additive and subtractive processes. For long-term
47 assessments, site stability analysis of geomorphological processes will likely entail integration of
48 the effects of many of the processes described in the following sections.

1
2 Site characterization and selection will play an integral role in assessing natural processes that
3 may impact the stability of the disposal facility. For new sites, applicants should characterize
4 the site to define the geomorphic, tectonic, and other hazards that may significantly impact site
5 stability. For existing sites that want to accept new waste, additional site characterization may
6 be needed if the waste is materially different (e.g., more long lived) from previously accepted
7 waste.

8 **5.1.1.1 Geomorphic Processes**

9
10 Geomorphic processes, such as mass wasting, slumping, land sliding, erosion, sinkhole
11 formation, and weathering, may impact the stability of an LLW disposal facility. A description of
12 the geomorphology of the site, including USGS topographic maps that emphasize pertinent
13 local geomorphic features, may be useful to identify processes, such as erosion, that may affect
14 long-term site stability. Erosion and weathering, in particular, are especially applicable to LLW
15 disposal. Fluvial (at more humid sites) and eolian (at more arid sites) erosion of engineered
16 covers is a common disturbance mechanism for disposal of long-lived waste. To mitigate
17 certain geologic processes, licensees may achieve long-term erosion protection with robust
18 engineered designs using a system of erosion controls and durable, appropriately sized rock
19 (NRC, 2002b). Long-term erosion protection is protection for thousands of years to possibly a
20 few tens of thousands of years. To achieve such long-term protection, the erosion controls
21 should be independent and redundant, and the rock should be resistant to weathering.
22 Avoidance of steep slopes and the use of low relief designs can reduce the impact of some
23 geologic processes (NRC, 2002b). As discussed in Section 5.3, licensees may consider
24 engineered barriers to mitigate the impact of many geologic processes.
25

26 The NRC staff expects erosive processes (fluvial and eolian) to be the most likely of all of the
27 disruptive processes to impact the long-term stability of most disposal facilities. Therefore, the
28 NRC staff recommends licensees develop robust erosion control designs using durable
29 materials, as discussed in Section 5.3. Robust erosion control designs are usually developed
30 based on the consideration of low-probability events, such as the PMP and corresponding PMF
31 (NRC, 2002b). The PMF is defined as the hypothetical flood that is considered to be the most
32 severe flood reasonably possible, based on (1) comprehensive hydrometeorological application
33 of the PMP, and (2) other hydrologic factors favorable for maximum flood runoff, such as
34 sequential storms and snowmelt. The return period of the PMP has been debated in technical
35 literature because there are few direct observational data. A comparison of PMF peaks with
36 historic floods in the United States yielded nine floods that exceeded 80 percent of the PMF but
37 none that exceeded the estimated PMF (Bullard, 1986). Similar data compiled for
38 approximately 20,000 gauging-station-years did not yield a flood that exceeded the calculated
39 PMF (Crippen and Bue, 1977). For specific streams, paleo-flood data may be available to
40 provide confidence that the computed PMF estimate is appropriately conservative. The return
41 period associated with the PMP has been estimated from one statistical analysis of historical
42 data at approximately 60,000 years (Koutsoyiannis, 1999). Koutsoyiannis cited the work of
43 others that estimated the return period of the PMP to be from 200,000 to 1×10^9 years, using
44 different approaches. The NRC staff considers the PMP to be a very unlikely event with respect
45 to LLW disposal and that the PMP is appropriate to use to produce a conservative design.
46

47 The general approach used to assess geomorphic processes will involve three general steps:
48 (1) identification of past geomorphic processes and estimation of their rates from stratigraphic

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

15
16 It should be noted that a site does not necessarily need to experience mass loss; a site may be
17 located in an accreting environment. Accreting environments are more favorable to long-term
18 stability as nature enhances the isolation of the waste from the environment by covering the
19 disposal facility over time. However, certain depositional processes may degrade the
20 performance of some types of erosion controls (such as diversion channels). Licensees may
21 use diversion channels at a site in an accreting environment to limit fluvial erosion and ensure
22 site stability. Even in a net depositional environment, the site may experience periods of both
23 deposition and erosion.

24 **5.1.1.2 Tectonic Processes**

25
26 Tectonic processes that can lead to long-term processes or events such as faulting, seismicity,
27 or volcanism, may impact the stability of an LLW disposal facility. Nevertheless, a variety of
28 factors should make tectonic processes generally less significant than the aforementioned
29 geomorphic processes. First, licensees should use the site selection and characterization
30 process to avoid areas of high tectonic activity. Second, LLW facilities are generally passive
31 buried systems that are more susceptible to gradual deterioration from degradation and
32 weathering than to discrete failure due to unlikely tectonic events. An exception would be
33 facilities that rely significantly on engineered barriers to meet the performance objectives,
34 especially resistive engineered barriers. A resistive engineered barrier is one that is reliant on
35 physical properties to prevent liquid flow or transport, such as a geomembrane or cementitious
36 barrier. A significant seismic event could result in cracking that would impact the ability of the
37 engineered barrier to limit water flow. The durability of the engineered barriers would need to
38 be assessed, as discussed in Section 5.3.

39
40 Licensees should assess the potential for subsurface geologic processes, such as faulting or
41 seismic activity, to affect the site and proposed disposal facility. They should review historically
42 recorded seismic information including recurrence intervals, magnitudes, and durations, as well
43 as factors that contribute to peak ground acceleration, such as underlying geologic structures
44 (e.g., active faults) and the stratigraphy and lithologies of the site. Licensees should evaluate
45 the predicted effects of seismic events on waste isolation. Reviewers should evaluate any
46 aspects of the disposal system designed to mitigate the potential effects of seismic events on
47 waste isolation. Additional guidance on reviewing information related to seismic events in waste
48 disposal is provided in NUREG-1804 (NRC, 2003c).

1 **5.1.1.3 Other Disruptive Processes**
2

3 Other natural processes and events can significantly impact the stability of an LLW disposal
4 facility. These may include, but are not limited to, climactic processes and climate change,
5 biological processes, and fires.
6

7 Climate and climate change have the potential to impact the stability of the disposal site. The
8 impact of natural cycling of the climate could range from minimal to severe, depending on the
9 location of the disposal facility. The type of waste that is disposed can influence how disruption
10 from climate and climate change should be included in the assessment. Climate change can
11 result in changes to the magnitude and duration of precipitation events, modification of the
12 number of freeze-thaw cycles, or other effects.
13

14 For conventional LLW inventory, licensees should limit unnecessary speculation about severe
15 climate change, such as glaciation. This type of event is envisioned as broadly disrupting the
16 disposal site region. For conventional LLW, the hazard from the inventory remaining after
17 500 years is expected to be relatively low. The dispersion and dilution associated with the
18 glaciation would further reduce doses. For LLW inventories that have low concentrations of
19 radioactivity, the impact from waste that has been disturbed by severe climate change would
20 likely be small compared to the impacts on humans from the event itself (i.e., the non-
21 radiological consequences should outweigh the radiological consequences). However, it is still
22 useful to communicate the sensitivity of the traditional LLW disposal facility performance to less
23 severe changes in climate, such as changes to annual average precipitation and temperatures.
24

25 For LLW inventories containing long-lived isotopes, the hazard from the inventory remaining
26 after 500 years may be significant. Therefore, licensees may need to evaluate the impact of
27 climate change on the disposal site taking into account reasonably conservative scenarios.
28 Climate change may not be gradual and continuous, as evidenced by a wide variety of
29 published information (Alley, 2000; Fricke, 1993; Jenkyns, 2003). The rate of change may be
30 just as important to establishing the risk as the magnitude of change. As previously discussed
31 in Section 2.0, the site suitability requirements do not allow for selection of sites where instability
32 precludes defensible modeling or assessment of long-term impacts.
33

34 Licensees should examine plausible scenarios for site evolution and characteristics in the site
35 stability analysis. For example, the erosion rate under a future, wetter climate may be
36 significantly larger than the present day. It should be noted that even small erosion rates can
37 amount to substantial thicknesses in the long term (e.g., a 0.5 mm/yr rate will reduce a cover's
38 thickness by half a meter in 1,000 years). However, the NRC staff believes that the magnitude
39 of the PMP and PMF is not likely to change significantly in a wetter climate, based on the
40 conservatism associated with the estimation of the PMP and the PMF.
41

42 Biological processes can impact the stability of the waste and the stability of the disposal
43 system. Biodegradation can affect the stability of waste containers and result in deterioration of
44 the wasteform, which can result in instability of the disposal system. The BTP on wasteform
45 describes test procedures and criteria to evaluate wasteform stability (NRC, 1991b).

46 Biointrusion into the waste, or into engineered covers over the waste, can increase infiltration to
47 the waste and contribute to the instability of the disposal system. Plants and animals may
48 create pathways in resistive barriers. The disruptive effects of biological processes tend to be
49 gradual but can be significant in some systems. Evapotranspiration or water balance covers

1 can depend strongly on vegetation to eliminate water. Therefore, licensees should consider the
2 impact of invasive species that have different root depths or growing patterns and water usage
3 on site stability and on the performance assessment. Climate change may affect pedogenesis
4 (i.e., soil development processes) and the type of cover vegetation. Fires, severe storms, and
5 ecological succession due to changing temperature and precipitation could influence the ability
6 of the vegetation to resist wind and water erosion and maintain a sufficient depth of cover over
7 the waste.

8
9 LLW facilities are generally not highly sensitive to the impact of fires, such as brush fires.
10 However, as mentioned above, vegetation can play an important role in reducing soil loss and
11 maintaining site stability, in particular for slopes and covers. Under extreme conditions, fires
12 may change the physical properties of the site soils and other cover materials. Strong fires
13 have been shown to impact durability of select rock types (e.g., silica based minerals deteriorate
14 after exposure to high temperatures) (Dorn, 2003). However, researchers at DOE's Hanford
15 Site directly evaluated the impact of fire on an engineered cover system and found the impact to
16 be minimal for their particular cover materials (Ward et al., 2009).

17 **5.1.2 Anthropogenic Processes**

18
19 Human activity may influence site stability both directly and indirectly. An example of a direct
20 influence is construction of a dwelling on the disposal facility. An example of an indirect
21 influence is acid rain generation, which could impact the durability of erosion control materials.
22 The intruder assessment examines the direct impact to an inadvertent intruder who unknowingly
23 disturbs the waste disposal facility. A licensee does not need to evaluate indirect impacts
24 associated with human activity at the disposal site because they would be difficult to define and
25 highly speculative. In addition, the direct impacts to the intruder should, in most cases, bound
26 the impacts to the general public (offsite) from anthropogenic disruption of the disposal facility
27 because there is comparatively less dispersion and dilution in the assessment of impacts to the
28 intruder, so the direct impacts will be greater. However, if site-specific intruder scenarios are
29 used that result in relatively limited exposures, then indirect processes may dominate the risk
30 and should be examined. A licensee does not need to consider anthropogenic climate change,
31 but should consider natural cycling of climates, if necessitated by the analysis timeframe for
32 their waste disposal actions. Section 4.0 provides guidance for performing the intruder
33 assessment.

35 **5.1.3 Subsidence and Differential Settlement**

36
37 Subsidence and differential settlement are very important for all types of waste disposal
38 because instability of the disposal site can result in unacceptable releases, regardless of the
39 overall stability of the disposal facility. Differential settlement was a key failure mode in earlier
40 LLW disposal sites, prior to the passage of 10 CFR Part 61 (NRC, 2007b). Subsidence and
41 differential settlement can lead to unacceptable releases because the processes can adversely
42 affect barrier performance (e.g., cracking of an engineered cover, creating a depression in the
43 cover resulting in localized ponding).

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

- 3
- 4 • Excessive void space in the waste or backfill
- 5 • Lack of compaction or improper compaction of waste, backfill, engineered or natural
- 6 materials
- 7 • Degradation of wasteforms, engineered barriers, and other structures
- 8 • Improper waste emplacement
- 9 • Alteration of natural materials (e.g., collapse of subsurface zones)
- 10 • Excessive or uneven loading of the disposal site or engineered cover
- 11 • Interaction of the disposal system with water
- 12

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

20 **5.2 Technical Assessment**

21

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

29 **5.2.1 Available Tools and Codes²**

30

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

42

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.

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

13
14 The University of Colorado and partners have created the Community Surface Dynamics
15 Modeling System (CSDMS) that provides (1) a modular modeling environment capable of
16 significantly advancing fundamental earth-system science, and (2) fully functional and useful
17 repositories for models, supporting data, and other products for educational and knowledge
18 transfer use (Syvitski et al., 2011). The CSDMS repository contains more than 160 models and
19 tools. The system includes 66 codes and 41 tools associated with terrestrial modeling.
20 Landscape evolution (CHILD, SIBERIA, Caesar, Erode, GOLEM, MARSSIM, and WILSIM),
21 eolian transport (Eolian Dune Model), and cryosphere (GC2D, ISGR, Ice Ages) codes are
22 included.

23 **5.2.2 Approaches for Assessment**

24
25 Licensees may use a variety of technical assessment methods to perform site stability analyses.
26 Because of the site-, facility-, and waste-specific nature of site stability analysis, the tools and
27 assessment techniques used may differ considerably from site to site.

28
29 The approaches may be design-based, model-based, or a combination of the two. Modeling
30 may play a more significant role for analysis of longer timeframes, due to the limited data to
31 support long-term performance of stability designs. It is important that licensees provide a
32 technical basis for the site stability analysis, regardless of the approach used. The technical
33 basis will likely be more extensive for analysis of longer timeframes than for shorter timeframes.
34 Model support is essential for site stability analysis. Licensees should develop model support
35 throughout the process, although the largest effort (comparable to model validation) is usually
36 completed at the end of the process. Model validation in the traditional usage is not possible for
37 analyses over long timeframes. Iteration may be necessary.

38
39

1 **Table 5-1 Summary of Applicability and Limitations of Erosion and Mass Wasting**
 2 **Codes for Long-Term Performance Assessment Evaluated in Walter and**
 3 **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

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

5
6
7
8

1
2 The site stability assessment should include the following general steps:
3

- 4 (1) Site description — Provide a description of the features of the site, facility, and waste
5 associated with stability. At a minimum, licensees must provide information required by
6 10 CFR Part 61, Subpart D (technical requirements for land disposal facilities). As
7 previously discussed, 10 CFR 61.50(a)(4)(iii) and 10 CFR 61.50(a)(4)(iv) provide specific
8 requirements with respect to tectonic and geologic processes. The site description can
9 include geologic and geomorphic characteristics that contribute to site stability. The site
10 description may also include geologic, geomorphic, and tectonic hazard assessments.
11
- 12 (2) Overall initial radiological risk screening — It may be possible to demonstrate, with a
13 conservative evaluation, that release of radioactive material, as a result of potential
14 instability, will not result in sufficient radiological risk (i.e., that the 10 CFR 61.41 and
15 10 CFR 61.42 performance objectives can still be met). If so, site stability analysis may
16 be limited to providing the screening assessment. In other words, a licensee can satisfy
17 10 CFR 61.44 if its screening assessment provides reasonable assurance that 10 CFR
18 61.41 and 10 CFR 61.42 will be met under disturbed conditions. Licensees should
19 select receptors and scenarios consistent with the guidance provided in Section 2.2.4
20 and Section 4.0. The screening assessment should be sufficiently conservative to
21 account for uncertainty.
22
- 23 (3) Process and event screening — Perform screening of disruptive processes and events
24 (consistent with guidance provided in Section 2.5). Processes and events can be
25 screened out of the assessment based on probability, consequence (as indicated in
26 Step 2 above), or risk-based criteria. Risk-based criteria combine probability and
27 consequence. Screening of disruptive processes and events based on consequence or
28 risk should consider the integrated effects of the processes or events, as discussed in
29 Section 5.1.
30
- 31 (4) Define scope of the assessment — The FEPs that cannot be screened out from the site
32 stability analysis should be used to define the scope of the assessment. Licensees can
33 compile the processes and events that cannot be screened into scenarios. They can
34 inform the scope of the assessment by considering the operating experience of
35 analogous sites and facilities. If there is uncertainty about whether a process or event
36 should be included, the NRC staff recommends erring on the side of inclusion. It is
37 generally more difficult to add processes and events at a later date in the analysis
38 process than it is to remove them from the assessment.
39
- 40 (5) Characterize information — Use the site description to determine what data are available
41 to complete the assessment and to identify the significant sources of uncertainty. The
42 type of information available is likely to depend on the timeframe being analyzed.
43 Interpretation of the available information, with the characteristics of the waste, disposal
44 facility, and site, will inform the approach that should be used for the assessment (e.g.,
45 model-based or design-based). The purpose of this step is to determine how much
46 information is available to support the assessment completed in Step 6.
47
- 48 (6) Perform assessment — The assessment may be performed with a model-based
49 approach (generally for long-lived wastes), a design-based approach (for short-lived or

1 long-lived wastes), or a combination of the two. The NRC staff expects that licensees
2 may use modeling to assess and develop designs. The steps provided below may be
3 completed in a different sequence. However, regardless of the order, most assessments
4 will include the following steps:
5

6 **a. Design-Based:**
7

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

15
16 **b. Model-Based:**
17

- 18 i. Define the model objectives.
- 19 ii. Develop or select the conceptual model.
- 20 iii. Document and provide the basis for assumptions.
- 21 iv. Develop the numerical model.
- 22 v. Parameterize the model.
- 23 vi. Calibrate the model.
- 24 vii. Verify the model.
- 25 viii. Characterize uncertainty.
- 26 ix. Provide model support.
- 27 x. Iterate, if necessary.

28
29 The elements listed above for design-based or model-based approaches are not unique
30 to site stability assessment for LLW disposal. Many information sources are available to
31 provide additional guidance, such as Section 2.0 of this document and NUREG-1573. In
32 addition, licensees may mix elements from design-based and model-based approaches.
33 For example, Appendix P of NUREG-1757 provides a description of how to risk-inform
34 the design-based approach. Risk-informing the design-based approach involves
35 performing technical analyses, such as sensitivity analyses, to test the robustness of the
36 design to unanticipated events and processes.
37

- 38 (7) Integrate — The site stability assessment will likely need to be integrated with the
39 performance assessment required by 10 CFR 61.41 and the intruder assessment
40 required by 10 CFR 61.42. If stability can be assured, then the level of integration is
41 minimal. However, if instability is projected, then licensees will need to evaluate the
42 significance of that instability in the performance assessment and intruder assessment.
43 For example, degradation of an engineered cover via erosion may lead to increased
44 water infiltration to waste in a disposal cell. The releases estimated in the performance
45 assessment should include nominal performance, as well as releases attributed to
46 instability of the waste, the disposal site, and the disposal facility. When the stability
47 assessment is based on both design and modeling, it is also important for a licensee to
48 document that the design has been integrated into the stability modeling.
49

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

4 **5.2.2.1 Design-Based Approach**

5
6 A licensee may use a design-based approach to site stability analysis to demonstrate site
7 stability for the associated timeframe. The design-based approach has been used successfully
8 for the management of uranium mill tailings, though the experience base is only tens of
9 decades. Section 5.3.2 presents information on analogs that suggests longer-term performance
10 should be achieved. Appendix E provides an example of the use of the design-based approach
11 to develop erosion protection measures for the management of uranium mill tailings. Section
12 5.3 of this document provides guidance on the use of engineered barriers for site stability
13 assessment. A licensee may use the guidance provided in Section 5.3, or alternatively, may
14 develop their own approach as long as the technical content of the steps listed in Section 5.3 is
15 included. Designs may use risk information, however, to mitigate long-term uncertainties,
16 conservative, robust designs may be beneficial irrespective of projected risk information. The
17 design-based approach may be supplemented with sensitivity analyses in order to better
18 characterize and understand uncertainties (see NUREG-1757, Volume 2, Revision 1, Sections
19 3.5.2 and 3.5.3). The following steps outline the design-based approach.

20
21 *Define the design objectives.* The primary design objectives are the time period over which
22 stability must be achieved and what instability, if any, is tolerable in order to ensure compliance
23 with the 10 CFR Part 61 Subpart C performance objectives. Waste characteristics and the risk
24 to the public, including an inadvertent intruder, will be the drivers of the design objectives. For
25 example, a licensee that wishes to dispose of only short-lived waste and small quantities of
26 long-lived waste may achieve protection of public health and safety by ensuring waste stability
27 for 500 years. The licensee may be able to demonstrate that insufficient radioactivity remains in
28 the disposal system to pose an unacceptable risk to a member of the public after that time.

29
30 *Develop or select the design.* After defining the design objectives, the licensee should develop
31 the design or select a design that has previously been demonstrated to achieve their objectives.
32 Because of the site-specific nature of LLW disposal, even previously utilized designs are likely
33 to require modifications for site-specific application. Section 5.3 presents information on rock
34 durability, for example, that is strongly influenced by local environmental conditions. Section 5.3
35 provides an acceptable process for selecting erosion protection materials.

36
37 *Document and provide the basis for assumptions.* Assumptions are a common part of design
38 and analysis. A licensee should document and provide a basis for assumptions that they have
39 used in developing or selecting their design. Regulators should review the documentation and
40 determine if adequate technical bases for the assumptions have been provided. Assumptions
41 should be internally consistent.

42
43 *Characterize or parameterize the design.* After a licensee has developed or selected a design,
44 they may need information in order to characterize the features of the design or provide
45 parameters that will be used to represent the performance of the design. For example, a design
46 may use natural and engineered materials. The licensee may need to consider the weathering
47 or degradation rate of those materials. The licensee may need to perform and document
48 experiments used to develop the design information, such as the thickness of a reactive wall.

1 Sufficient documentation should be provided to allow for independent verification of the results.
2 If a licensee uses information from generic sources to parameterize the design, they should
3 demonstrate that the information is relevant to the site-specific application.
4

5 *Assess the expected performance of the design.* Verification of the design involves technical
6 assessment of the performance of the design over the range of disruptive processes and events
7 expected to influence the design. A licensee should clearly identify over what range of
8 conditions the design is expected to perform and over what range of conditions the design may
9 fail. This information is useful to regulators and other stakeholders if future conditions are to
10 occur that may have been unforeseen during the design process. A licensee or regulator may
11 use independent confirmatory analyses or modeling in order to verify the design.
12

13 *Provide support for the design.* A licensee must provide adequate support for the design prior
14 to implementation of the design. Types of support for engineered designs are similar to the
15 types of support provided for models, as discussed in Section 2.2.3 (e.g., tests, experiments,
16 field studies, and analogs). In addition, support for designs may also include the experience
17 base for the particular design, such as the number of locations where it has been used and for
18 how long. Unique or novel designs, which may be necessary for particular applications, are not
19 to be discouraged but they will have additional uncertainty as to whether they will achieve the
20 design goals. A licensee should provide additional support for the performance of a novel
21 design compared to what would be provided for a standard design that is expected to perform
22 for a similar time period. The support for the design at the time of implementation will not have
23 information from the actual performance of the design. Therefore, the overall design process
24 may need to be iterative as monitoring and performance confirmation data are collected.
25

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

34 **5.2.2.2 Model-Based Approach**

35
36 A licensee may also use a model-based approach for performing the site stability analysis for
37 the associated timeframe. The model-based approach is used to evaluate the FEPs that may
38 affect the stability of the site and determine if the effects are significant. The model-based
39 approach may determine that the impacts are:
40

- 41 • Insignificant - adequate site stability has been achieved irrespective of the FEPs
42 associated with site stability, or
- 43 • Significant - site stability has not been achieved.
44

45 A licensee may undertake a variety of actions if site stability is not demonstrated. They may
46 refine their modeling and the refined model may demonstrate that the projected FEPs have
47 insignificant impacts. As a result of their modeling, the licensee could implement design

1 changes to achieve stability, or they may conclude that the site does not have adequate stability
2 to be suitable for the type of waste proposed for disposal at the site. Inventory limits may be
3 used to mitigate the risks and uncertainties associated with site instability
4

5 The steps involved in the model-based approach to site stability assessment provided in Section
6 5.2.2 are similar to the steps to develop a performance assessment. Therefore, a licensee
7 should review the guidance provided in Section 2.0 when using a model-based approach to site
8 stability assessment. Appendix E provides an example of using a model-based approach to site
9 stability assessment. As discussed in Section 2.2.3 and Section 5.3.2, model support is
10 essential to any type of model-based approach. The NRC staff strongly recommends natural
11 analogs and other forms of evidence of the long-term stability of the site.
12

13 A number of tools and codes are available to licensees to support site stability modeling. The
14 field of geomorphology has evolved considerably over the last half century and numerous
15 technologies are available today to facilitate site stability analysis, including various programs
16 such as hydrologic codes, erosion codes, and landscape evolution codes (e.g., CHILD and
17 SIBERIA). Although the uncertainties associated with such landscape modeling are often large,
18 licensees can use modeling to gain insights and perform site stability assessments.
19

20 Licensees should consider the following technical issues when developing the scope of a
21 model-based approach to site stability assessment:
22

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

5.2.3 Uncertainty

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

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

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

5.3 Engineered Barriers for Site Stability

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

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

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

5 **5.3.1 Existing Guidance**

6
7 The NRC staff believes that existing guidance developed for analogous programs (e.g., uranium
8 mill tailings, decommissioning) is applicable to the design of engineered barriers for the stability
9 of LLW disposal facilities. The processes and events that may disrupt LLW facilities are
10 essentially identical to those that may impact a uranium mill tailings disposal facility or a
11 decommissioned site. The main exception is that some LLW disposal facilities could contain
12 higher concentrations and quantities of long-lived waste. Considerations for the design of
13 engineered barriers for long-lived waste are provided in Section 5.3.2. Existing guidance is
14 focused on cover design, particularly material durability. The focus of stability analysis in waste
15 disposal has been on erosion protection. The NRC staff plans to periodically assess the
16 sufficiency of guidance in this area and supplement it when necessary.

17
18 Engineered barriers are distinct and separate from institutional controls. Used in the general
19 sense, an engineered barrier could be one of a broad range of barriers with varying degrees of
20 durability, robustness, and isolation capability. Generally, engineered barriers are passive,
21 man-made structures or devices intended to enhance a facility's ability to meet the performance
22 objectives. Engineered barriers are usually designed to inhibit water from contacting waste,
23 limit releases of radionuclides (e.g., through groundwater, biointrusion, or erosion), or to mitigate
24 doses to inadvertent intruders. Engineered barriers can serve a variety of functions; therefore,
25 they have markedly different technical considerations and designs. The NRC staff expects that
26 the main type of engineered barrier used for LLW disposal will be engineered covers.
27 Engineered covers can be further classified into conventional (resistive) covers and water
28 balance (evapotranspiration) covers. Each of these types of covers may have erosion control
29 functions. The following sections further discuss these types of covers.

30
31 Section 3.5 of NUREG-1757, Volume 2, provides guidance on a risk-informed, graded approach
32 to the design and evaluation of engineered barriers (NRC, 2006). High-level guidance on
33 engineered barriers is provided in NUREG-1573 for general application to LLW disposal.
34 NUREG-1573 contains a bibliography organized by different topics, including Appendix C on
35 engineered and natural barriers. There are a broad range of engineered barriers for stability,
36 with varying degrees of durability and robustness. Engineered barriers for LLW disposal
37 stability should be passive (i.e., they should perform without reliance on active monitoring and
38 maintenance). Licensees should provide an appropriate technical basis for engineered barriers
39 providing significant performance. The following steps are the main steps of an appropriate
40 technical basis for engineered barriers, as described in NUREG-1757:

- 41
- 42 • Describe the design, features, and functionality of the engineered barriers.
 - 43 • Provide the technical basis that the performance of the barriers will allow a licensee to
44 demonstrate that the performance objective will be met, considering the degradation
45 mechanisms, including consideration of combined and synergistic effects resulting from
46 the real-world conditions expected for the barriers.

- 1 • Describe uncertainty in parameters and models used in the assessment of barrier
2 performance and the design of engineered barriers.
- 3 • Demonstrate the suitability of numerical models for the estimation of engineered barrier
4 performance.
- 5 • Perform parametric or component sensitivity analysis to identify how much degradation
6 of the engineered barrier would result in noncompliance.
- 7 • Provide model support for the engineered barrier performance (e.g., analogs,
8 experiments, engineering calculations to demonstrate reasonableness of the results).
- 9 • Provide QA/QC for the data collection, design, construction, and analysis of engineered
10 barriers.

11
12 These steps apply to engineered barriers used to support demonstration of compliance with
13 10 CFR 61.41 and 10 CFR 61.42, as well as for site stability. Model support for engineered
14 barrier performance is essential. Model support, as discussed in Section 2.2.3, can come in
15 many different forms, including but not limited to analogs, laboratory experiments, field
16 experiments, and formal and informal expert judgment. The basis for why a barrier is expected
17 to perform the desired function is essential for a licensee and other stakeholders to have
18 confidence in the future performance of the barrier. For engineered barriers that are estimated
19 to have long-term performance (e.g., thousands of years), licensees should consider natural
20 analogs in order to provide confidence that the estimates are reasonable. Extrapolating short-
21 term observations to estimate long-term performance can result in a significant uncertainty in
22 long-term barrier performance. Standard approaches implicitly assume that the initial conditions
23 persist; however, the actual application of a barrier may be more appropriately viewed as an
24 evolving component of a larger dynamic system (Vaugh and Richardson, 1997). In addition,
25 inaccurate conceptualization of degradation mechanisms and their interaction can be a source
26 of significant error. Adequate model support can help reduce the impact of these uncertainties.
27 NUREG-1757 provides examples of analogs for cement performance (wasteform stability),
28 durability of earthen covers, and riprap durability (site stability) (NRC, 2006). NUREG-1757 also
29 summarizes the degradation mechanisms of common engineered barriers, including engineered
30 covers such as resistive covers, water-balance covers, and erosion control covers. Section
31 3.5.5 of NUREG-1757 provides a summary of reference information related to engineered cover
32 design and performance.

33
34 One of the most common barriers used to ensure stability in waste disposal facilities, especially
35 for near-surface disposal of long-lived waste, is an erosion protection cover. As mentioned in
36 Section 5.2.2.1, NUREG-1623 may be useful to licensees because it provides methods,
37 guidelines, and procedures that the NRC staff considers to be acceptable for designing erosion
38 protection at uranium mill tailings sites (NRC, 2002b). The main elements to developing an
39 engineered barrier for erosion protection in waste disposal are:

- 40
- 41 • Selection of proper rainfall and flooding events
- 42 • Selection of appropriate parameters for determining flood discharges
- 43 • Computation of flood discharges using appropriate and/or conservative methods
- 44 • Computation of appropriate flood levels and flood forces associated with the design flood
45 discharge

- 1 • Use of appropriate methods for determining erosion protection needed to resist the
2 design discharge
- 3 • Selection of a rock type for the riprap layer that will be durable and capable of providing
4 the required erosion protection for the required timeframe
- 5 • Placement of riprap layers in accordance with accepted engineering practice and in
6 accordance with appropriate testing and quality assurance controls
7

8 The NRC staff considers that the guidance provided for design of erosion protection systems for
9 management of uranium mill tailings is applicable to the stability of LLW disposal facilities, and
10 may be used for nearly all types of erosion protection designs. However, for high
11 concentrations and large quantities of long-lived waste (as discussed in Section 5.3.2),
12 licensees should place greater emphasis on rock durability, and additional considerations may
13 be necessary. Erosion protection designs may take many different forms. Many designs use a
14 durable rock cover; however, some combine vegetation or employ multiple layers of differing
15 materials (i.e., a composite cover) or rock mulches.
16

17 The main design considerations of an erosion protection cover using rock can be separated into
18 two main areas: (1) appropriate sizing of the rock, and (2) assurance of the durability of the
19 cover materials. NUREG-1623 provides methods for sizing rock for an erosion protection cover
20 (design based on the PMP). Licensees should size the rock to ensure it will stay where it is
21 placed; they should then ensure that the rock will not degrade significantly (i.e., it will stay close
22 to its initial size). In order to maintain its design size, appropriately sized rock should not
23 experience significant mass loss from weathering or experience significant cracking.
24

25 Rock durability is defined as the ability of a material to withstand forces of weathering. Factors
26 that affect rock durability are (1) chemical reactions with water, (2) saturation time, (3) the
27 temperature of the water, (4) scour by sediments, (5) windblown scour, (6) wetting and drying,
28 and (7) freezing and thawing. Chemical weathering and mechanical weathering may reduce the
29 effectiveness of a rock cover for erosion protection. Chemical weathering is generally a slow,
30 continuous process that usually occurs in the presence of water. Mechanical weathering is a
31 process that can lead to deterioration of the rock without chemical alteration. The most
32 prevalent mechanical weathering processes are (1) frost action and freeze-thaw activity, (2) salt
33 crystallization, migration, and hydration, (3) water sorption, (4) mineral hydration, (5) wetting and
34 drying cycles, (6) abrasion by wind, water, and mechanical means, and (7) temperature-induced
35 expansion and contraction of mineral grains (NRC, 1982c). Comparing the latter processes with
36 the factors that affect rock durability demonstrates that mechanical weathering is a dominant
37 degradation process. The individual weathering mechanisms are likely to be specific to the rock
38 type selected and the weathering processes at the site. Weathering processes and rates are
39 strongly influenced by climatic conditions. Figure 5-3 provides a macroscale relationship of
40 climatic variables, environments, and rock weathering agents.
41

42 An engineered cover for LLW disposal may have more than one design goal. For example, in
43 addition to providing site stability, the engineered cover may be used to reduce infiltration.
44 Licensee should ensure all design goals are achieved realizing that some decisions may have
45 competing influences on the design goal. For instance, using large rock may promote site
46 stability but may increase infiltration compared to other erosion protection designs such as using
47 rock mulch.
48

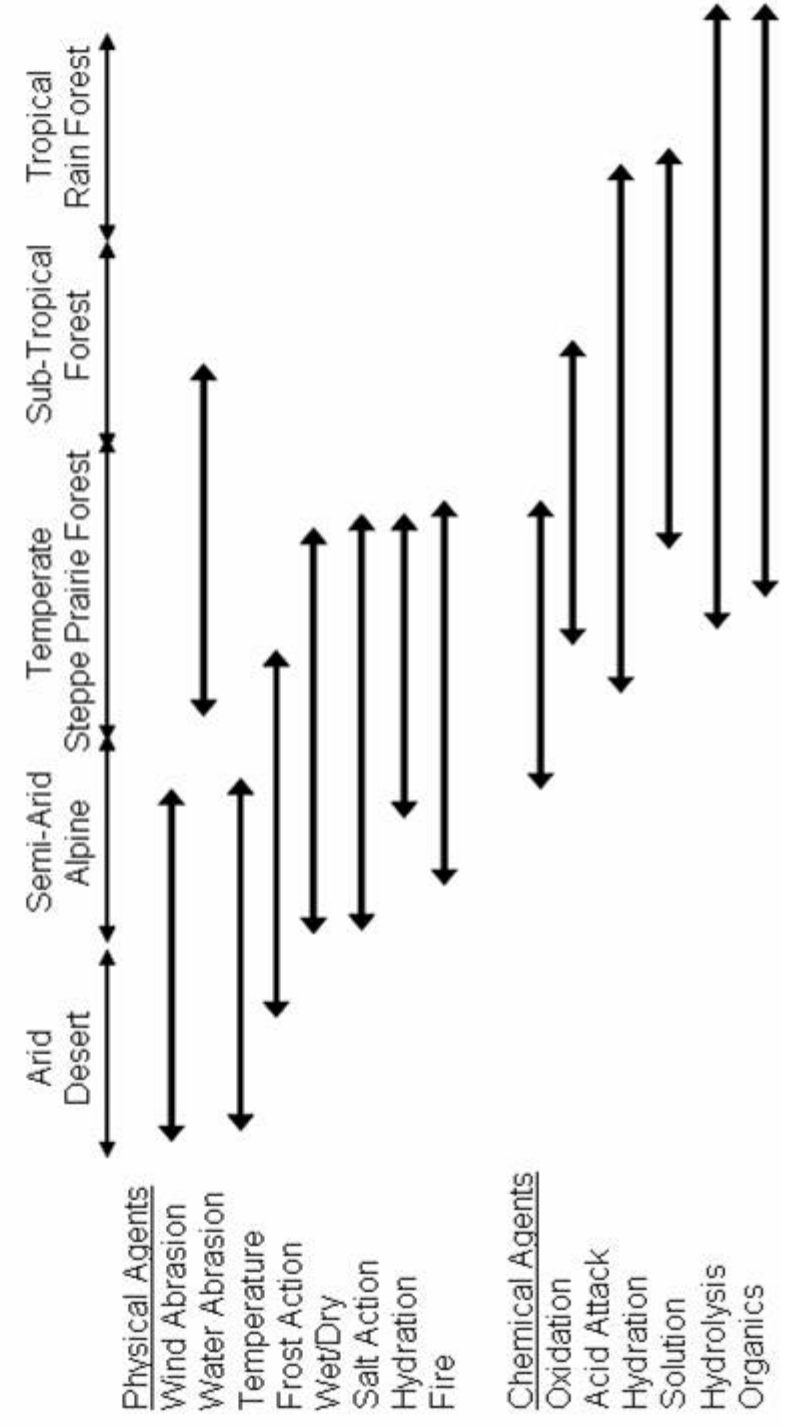


Figure 5-3 Macroscale Relationship between Climatic Variables, Environments, and Rock Weathering Agents: Occurrence of Weathering as a Function of Climate (NUREG/CR-2642)

1 As discussed in Appendix P “Example of a Graded Approach for Erosion” to NUREG-1757, a
2 licensee should conduct three evaluations of rock durability to provide multiple and
3 complementary lines of evidence and greater confidence in rock durability. The three
4 evaluations are for (1) rock durability testing and scoring, (2) absence of adverse minerals and
5 heterogeneities, and (3) evidence of resistance to weathering.
6

7 First, licensees should conduct rock durability testing and scoring. They should test and
8 evaluate potential rock sources to ensure that rock used for erosion protection remains effective
9 for the required timeframe. NUREG-1623 (NRC, 2002b) presents a procedure for determining
10 the acceptability of a rock source. In general, rock durability testing is usually performed using
11 standardized test procedures, such as those developed by ASTM and published and updated in
12 ASTM’s *Annual Book of ASTM Standards*. The scoring procedure indicates that rock scores of
13 80 percent or greater indicate a high-quality rock for most applications (e.g., decommissioning
14 sites for 1,000 years). Long-lived waste would generally require very high-quality rock, higher
15 than necessary for most decommissioning applications.
16

17 Second, the absence of adverse minerals and heterogeneities is essential. Licensees should
18 use analyses (such as petrographic analyses) to establish the absence of adverse minerals that
19 could cause rapid degradation of the rock, such as clays, olivine, or calcite cement. If adverse
20 minerals are present, licensees should evaluate their potential effect on the weathering of the
21 rock and on weathering rates.
22

23 Third, licensees should provide evidence of resistance to weathering, using direct evidence from
24 the selected rock source whenever possible. For example, weathering rind thickness and
25 alteration of minerals and rock properties from exposures of the weathered rock source can
26 provide insights on the extent and nature of future weathering. Table 5-2 provides general
27 characteristics of rocks related to weathering resistance (NRC, 1982c). Some characteristics
28 are favorable with respect to chemical weathering and unfavorable with respect to mechanical
29 weathering, and vice versa. Indirect evidence from natural and archeological analogs should
30 also be used, as discussed in Section 5.3.2.

31 **5.3.2 Long-Term Considerations**

32
33 Disposal of long-lived waste introduces additional complexity and uncertainty with respect to site
34 stability. A disposal facility containing long-lived waste may be exposed to (1) more extreme
35 conditions, as well as more cycles of extreme conditions, (2) greater uncertainty because of
36 more limited performance and observational data, and (3) greater difficulty in obtaining relevant
37 information. Because of the increased uncertainty inherent in longer-term predictions, the
38 design of engineered barriers for stability of long-lived waste relies on conservative designs.
39 Licensees should use the following elements in their design of engineered barriers for long-lived
40 waste:
41

- 42 • multiple, independent, and redundant barriers
 - 43 • conservative approaches
 - 44 • very high quality and durable materials
- 45
46

Table 5-2 Weathering Resistance and Susceptibility Related to Weathering Type and Rock Properties

	Chemical Weathering		Physical Weathering	
	Durable	Nondurable	Durable	Nondurable
Mineral Composition	<ul style="list-style-type: none"> - Uniform mineral composition - High silica content - Low metal ion content (Fe-Mg), low biotite - High orthoclase, Na feldspars - High aluminum ion content 	<ul style="list-style-type: none"> - Mixed/variable mineral comp. - High CaCO₃ content - Unstable primary igneous minerals - Low quartz content - High calcic plagioclase - High olivine 	<ul style="list-style-type: none"> - High feldspar content - Calcium plagioclase - low quartz content - CaCO₃ - homogeneous composition 	<ul style="list-style-type: none"> - High quartz content - Na plagioclase - Heterogeneous composition
Texture	<ul style="list-style-type: none"> - Fine grained dense rock - Uniform texture - Crystalline - Clastics - Gneissic 	<ul style="list-style-type: none"> - Coarse-grained igneous - Variable textural features - Schistose 	<ul style="list-style-type: none"> - Fine grained (general) - Uniform texture - Crystalline, tightly packed clastics - Gneissic - Fine-grained silicates 	<ul style="list-style-type: none"> - Coarse grained - Variable texture - Schistose - Coarse-grained silicates
Porosity	<ul style="list-style-type: none"> - Large pore size, low permeability - Free draining - Low internal surface area 	<ul style="list-style-type: none"> - Small pore size, high permeability - Poorly draining - High internal surface area 	<ul style="list-style-type: none"> - Low porosity, freely draining - Low internal surface area - large pore diameter - free draining 	<ul style="list-style-type: none"> - High porosity, poorly draining - High internal surface area - Small pore diameter
Bulk Properties	<ul style="list-style-type: none"> - Low adsorption - High compressive and tensile strength - Fresh rock - Hard 	<ul style="list-style-type: none"> - High adsorption - Low strength - Partially weathered rock - Soft 	<ul style="list-style-type: none"> - Low adsorption - High strength with good elastic properties - Fresh rock - Hard 	<ul style="list-style-type: none"> - High adsorption - Low strength - Partially weathered rock - Soft
Structure	<ul style="list-style-type: none"> - Strongly cemented, dense grain packing - Siliceous cement - Massive 	<ul style="list-style-type: none"> - Poorly cemented - Calcerous cement - Thin bedded - Fractured cracked - Mixed soluble and insoluble minerals 	<ul style="list-style-type: none"> - Minimal foliation - Clastics - Massive formations - Thick bedded sediments 	<ul style="list-style-type: none"> - Foliated - Fractured, cracked - Thin bedded - Mixed soluble and insoluble minerals
Representative Rock	<ul style="list-style-type: none"> - Igneous varieties (acidic) - Metamorphics (other than marbles) - Crystalline rocks - Rhyolite, granite, quartzite, gneisses - Granitic gneiss 	<ul style="list-style-type: none"> - Calcerous sedimentary - Poorly cemented sandstone - Slates - Limestones, basic igneous, clay-carbonates - Marble, dolomites - Carbonates, schists 	<ul style="list-style-type: none"> - Fine-grained granites - Some limestones - Diabases, gabbros, some coarse-grained granites - Quartzite (metamorphic) - Strongly cemented sandstone - Slates, granitic gneiss 	<ul style="list-style-type: none"> - Coarse-grained granites - Poorly cemented sandstone - Many basalts - Dolomites, marbles - Soft sedimentary - Schists

1 **5.3.2.1 Conventional (Resistive) Covers**
2

3 Licensees can use conventional covers for different design functions. However, with respect to
4 site stability, the most likely use of a conventional cover is for erosion protection. Designs for
5 sites with relatively short-lived waste are expected to be simpler than designs for sites with
6 waste that will remain hazardous until or beyond the end of the compliance period. Design
7 concepts for the end of the compliance period and for the performance period should include
8 the use of oversized rock and overthickened rock layers, use of the PMF, and consideration of
9 more stable structures such as low slopes and blending with local topography. By using
10 multiple, independent, and redundant barriers licensees can reduce the impact from the
11 unanticipated failure of a single barrier.
12

13 One example of the use of multiple barriers for an erosion control system could include one or
14 more of the following types of erosion controls:
15

- 16 • The riprap layer for the top slopes and side slopes of the closure covers could be
17 designed to resist the PMP and PMF.
- 18 • The top of the covers could be sloped to drain entirely in one direction, minimizing the
19 flows that would enter gullies that form in areas that are not designed for drainage
20 downstream of the covers.
- 21 • The site could be optimally graded to enhance drainage, and diversion channels could
22 be constructed to convey runoff to noncritical locations.
- 23 • Downstream gullies could be armored with very large rock to prevent further gullying and
24 nickpoint migration.
- 25 • Diversion channels could also be constructed upstream of the covers to divert flows
26 away from the covers or from potential critical gully locations.
27

28 Licensees may need to consider the natural cycling of climates in the design for sites intended
29 for long-lived waste disposal. In some locations (e.g., more northern), glacial and interglacial
30 cycles may result in glacier development and migration over a LLW disposal facility. It is
31 beyond current technology and understanding to design a near-surface facility to withstand such
32 forces. In more northern locations, the assessment should focus on the risks following
33 disruption of the design. Licensees may consider natural analogs to estimate the amount of
34 waste dispersion associated with those processes, and therefore, the risk. Stylized, conditional
35 dose assessments may also be useful. In more southern geographic locations, the impact of
36 natural cycling of climates may be less severe and may be confined to effects such as
37 increased precipitation and cooler temperatures (e.g., more freeze-thaw cycling). Licensees
38 should examine the durability of erosion control materials over the range of projected future
39 climate states. The use of the PMP and PMF for erosion protection design may mitigate the
40 need to consider future climate states because these parameters represent maximum events.
41 The PMP approach approximates the maximum rainfall that is physically possible, and the PMF
42 is a hypothetical flood that is considered to be the most severe reasonably possible (NUREG-
43 1623, p. 10). Climates that are arid now and more likely to be arid in the future are typically
44 preferable over wetter climates. Low amounts of water reduce chemical and mechanical
45 weathering.
46

1 Licensees should consider the following when selecting and justifying the long-term durability of
2 erosion protection materials:
3

- 4 • Selection of highly durable rock—Select only a highly durable rock type with a mineral
5 that is most resistant to chemical weathering, such as quartz. This would favor a
6 metamorphic quartzite or a sedimentary orthoquartzite with a high percentage of quartz
7 grains (99 percent) cemented by quartz. Rock types that can easily alter to clay over the
8 timeframe considered, such as feldspars, should not be used. This may eliminate many
9 rock types. Locally-available, highly durable rock is preferable because it has a higher
10 likelihood of being in equilibrium with the disposal environment.
11
- 12 • Selection of a homogeneous rock source—Select a rock unit that will result in riprap
13 pieces that are homogeneous and free of heterogeneities, such as bedding planes, thin
14 shale layers, or joints. Heterogeneities that can allow access of water can contribute
15 significantly to mechanical weathering, such as freeze-thaw.
16
- 17 • Reliance on natural analogs and weathering rate studies—Evaluate natural analogs and
18 obtain applicable weathering rate studies, if available, to justify the durability of the
19 selected rock.
20
 - 21 – Weathering rate studies: Obtain weathering rate study data over relevant
22 timeframes, to the extent available, recognizing any uncertainties in the studies.
23 Weathering rate data may be estimated from laboratory data complemented with
24 field observations. If laboratory data are generated, use caution in extrapolating the
25 data to field performance because mineral weathering does exhibit scale
26 dependence (Drever and Clow, 1995). Weathering rates can also decrease
27 exponentially with time, as the most vigorous attack usually occurs early in the
28 weathering process. Comparative data on natural materials may help with material
29 selection, such as that shown in Table 5-3 (Brookins, 1984) or in Table 6.7 of
30 NUREG/CR-2642, “Long-Term Survivability of Riprap for Armoring Uranium Mill
31 Tailings and Covers: A Literature Review” (NRC, 1982c). Comparative data show
32 the relative durability of different materials in a common test. Various compilations of
33 research on weathering rates have been developed (e.g., Colman and Dethier,
34 1986). Use weathering rate data that is representative of the estimated future
35 exposure conditions because weathering rates can be very sensitive to exposure
36 conditions. For example, one of Cleopatra’s Needles (a granite obelisk) survived
37 very well in over 3,000 years of exposure in arid conditions in Egypt but weathered
38 heavily in under 100 years after being moved to New York City.
39
40
41

1 **Table 5-3 Comparison of Chemical Durability (Soxhlet Test) of Waste Glass and**
 2 **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

3 Source: Brookins, 1984

4 ¹ Represents mass loss in the Soxhlet test

- 5
- 6 - Natural analogs: Use natural analogs to provide confidence in the long-term
 7 durability of the materials selected. Use natural analogs for the specific rock type
 8 proposed and from the region of the disposal facility, instead of more distant
 9 examples, because local materials with demonstrated long-term durability will
 10 provide the most direct link to long-term performance. However, more distant
 11 examples may be useful to address the durability of the materials under a more
 12 diverse range of exposure conditions. Quaternary glacial striations on quartzites and
 13 dating of very old rock surfaces may also be useful. Research is ongoing using
 14 cosmogenic dating to estimate the ages of natural materials that have not weathered
 15 significantly over very long time periods. For long-term stability, engineered systems
 16 should mimic durable natural systems as much as feasible. The comparison of
 17 engineered systems to natural systems should address material properties as well as
 18 how the materials are emplaced and distributed to achieve stability.

19

20 For a variety of reasons, certain Quaternary glacial features have the potential to be
 21 a very good source of natural analogs. The features of greatest potential value
 22 include glacial striations, polished rock surfaces, and glacial erratics. In particular,
 23 glacial striations (i.e., fine scratches on a bedrock surface that can be less than a
 24 millimeter in depth) and polished rock surfaces are delicate features that could easily
 25 be removed by weathering. Preservation of such vulnerable features over long time
 26 periods demonstrates a significant resistance of the rock to weathering. Glacial
 27 features (found in various climates today) are also fairly common in a range of
 28 different rock types, which makes them reasonably available for use as analogs.
 29 Glacial features have been exposed to a range of climates during the past thousands
 30 of years since their formation. Finally, licensees do not need to determine the
 31 precise age of the features in order to use them as a natural analog for a LLW
 32 facility. In the absence of available specific dating studies, a general assumption can
 33 usually be made that the features are the result of the last glacial period, which

1 ended about 10,000 years ago. Fortuitously, the general 10,000 year age
2 assumption coincides with the 10,000 year protective assurance period for a LLW
3 facility.

- 4
- 5 - Historic analogs: Preliminary analyses and observations by the NRC staff and
6 consultants have indicated that many manmade sites exist that demonstrate the
7 long-term stability of both manmade structures and naturally occurring features.
8 Many of these analog sites are located in the United States and consist of structures
9 such as Native American earthen burial mounds, Native American ruins, and rock
10 features. Many of these sites have been dated and have been shown to have
11 remained intact for thousands of years. Licensees can use studies of the long-term
12 survivability of such features to demonstrate the potential for manmade sites, such
13 as LLW waste disposal facilities, to remain intact for very long periods of time without
14 the need for ongoing active maintenance. For example, the Sarsen stones of
15 Stonehenge may provide data for orthoquartzites.

16

17 The benefits of historic or archeological analogs are that the ages of rock carvings, monuments,
18 or buildings are usually fairly well known and can demonstrate preservation under known
19 climates and time periods. Furthermore, many potential analogs might be available for a range
20 of rock types. While many of these analogs can demonstrate preservation for hundreds or
21 thousands of years, the timeframe is less than the 10,000 year protective assurance period.
22 However, if available, historic or archeological analogs can complement natural analogs by
23 providing a variety of evidence that together increase the confidence in the ability of a rock type
24 to resist significant weathering over long time periods.

25

26 Although direct evidence of material durability from the site or site region is preferable, licensees
27 can also use indirect evidence from other locations where the general rock type is similar to the
28 selected rock source, considering differences in environmental conditions. In some cases the
29 durability may be sensitive to the exposure conditions while in other cases it may be less
30 sensitive or insensitive. For example, licensees could use evidence of durability from a diabase
31 igneous rock-type found in Europe to provide insights on a diabase rock-type source in
32 Maryland because the general mineralogy of diabase is similar, regardless of the location. This
33 approach allows the use of datable natural or archaeological and historical rock sites, which
34 could provide general evidence of rock weathering rates or time periods during which rock types
35 have remained resistant to weathering. For example, a licensee could use many datable
36 archaeological sites, such as Stonehenge (constructed about 4,000 years ago of diabase and
37 silica-cemented sandstone); Hadrian's Wall (constructed by the Romans over 2,000 years ago
38 of primarily diabase); and numerous buildings, monuments, and megaliths in Europe, to
39 demonstrate that these rock types have been resistant to weathering over time periods that
40 exceed thousands of years.

41

42 Historical evidence can also provide useful insights on the durability of certain rock types. One
43 example is the comparison of dated Civil War photographs of diabase outcrops in Devil's Den at
44 the Gettysburg National Military Park to present-day conditions of the same outcrop. A licensee
45 could demonstrate with such a comparison that this diabase has been resistant to weathering
46 for about 150 years. Similarly, dated grave markers or historical buildings made from the
47 selected rock source or a similar rock type can also provide evidence of resistance to
48 weathering for 100–200 years. Appendix A to NUREG/CR-2642 provides additional information

1 on rock weathering, durability, and examples of analogs that provide insights on general
2 weathering rates of various rock types (NRC, 1982c).

3
4 A test wall of building stones was constructed in 1948 in Washington, DC and in 1977 it was
5 moved to the National Institute of Standards and Technology in Gaithersburg, MD (Stutzman
6 and Clifton, 1997). This test wall provides the opportunity to study the effects of weathering on
7 different types of stones under identical exposure conditions and the durability of different
8 materials. Imaging and petrological studies have been performed to characterize texture and
9 mineralogy. Correlation of mineralogical and microstructural features to stone performance
10 provides information for estimating the long-term durability of natural materials. The wall
11 contains 2,352 individual samples of stone: 2,032 domestic stones from 47 States and 320
12 stones from 16 foreign countries. Over 30 distinct types of stones are represented, including
13 marble, limestone, sandstone, and granite. Data from this project are limited at this time and
14 are likely to be uncertain but may provide licensees another line of evidence for rock durability.

15 **5.3.2.2 Evapotranspiration Covers**

16
17 Evapotranspiration (ET) covers, use the natural processes of evaporation and transpiration to
18 remove water from the cover. Although evaporation and transpiration can remove water from
19 the conventional covers discussed in Section 5.3.2.1, it is primarily the layers of low permeable
20 material present in the conventional covers that limit water from reaching the waste. In contrast,
21 ET covers rely more heavily on evaporation and transpiration to limit water from reaching the
22 waste. The performance of ET covers depends on many factors, especially the climate, soil
23 hydrology, fauna, and plant ecology at a site. ET covers may be used in a variety of settings,
24 but may be most effective in arid or semi-arid climates with high potential evapotranspiration.

25
26 Licensees should develop a design for an ET cover that is effective over the range of expected
27 natural and ecological conditions. Natural and ecological conditions are inherently variable over
28 the timeframe of most LLW disposal analyses. With effective design and development, ET
29 covers may be very effective, especially in arid and semi-arid climates. In humid climates, ET
30 covers may be effective at managing a substantial fraction of the infiltration but may not achieve
31 design goals. Infiltration may exceed evapotranspiration in humid climates or in colder climates,
32 where a large fraction of infiltration may occur as snowmelt when evapotranspiration is low.
33 Therefore, one of the major lessons learned, albeit not related to physical degradation, is that
34 design of an ET cover must consider natural and ecological variability over the analyses
35 timeframe (Benson et al, 2011).

36
37 Licensees should be aware that physical, biological, and chemical processes can induce
38 changes in the structure, physical, and biological characteristics of covers that are intrinsic to
39 their proper functioning as barrier systems. Degradation processes occur over a broad range of
40 time scales and include, but are not limited to, climatic variability, plant succession, geomorphic
41 processes, pedogenesis, anthropogenic impacts, erosion, microbial processes that affect barrier
42 materials and drains (e.g., biofouling), and geochemical processes. An example of
43 unanticipated ecological consequences is the development of deeper rooted plant species that
44 result in pathways for moisture that are below the design zone for moisture storage and
45 removal.

46
47 Engineered systems evolve towards a natural equilibrium. Licensees should recognize that soil
48 properties may change quickly, and therefore, should minimize the consequences of these

1 changes by designing and constructing covers that mimic longer-term conditions that are
2 congruent with nature. Cover degradation attributable to pedogenesis and ecological change
3 should be recognized as an inevitable, fairly predictable, natural succession. In some cases,
4 natural pedogenesis and ecological succession can lead to improved system performance over
5 time. Therefore, performance will be steadier over time when licensees design engineered soil
6 layers and vegetation to more closely resemble the characteristics of natural systems. A
7 licensee should determine the function of each ET cover component (e.g., use of plants and
8 their roots to stabilize the cover of a site). Licensees should develop techniques to understand
9 the magnitude and direction of natural changes anticipated to occur. One approach is to
10 evaluate natural analogs. General strategies that a licensee may use to minimize the negative
11 impacts of degradation processes include:

- 12
- 13 (a) Attention to construction QA; QA is especially important to the successful short-term
14 performance of the cover
- 15 (b) Identification of the phenomena that have the greatest impact on total system
16 performance
- 17 (c) Analysis of each component within the system context
18

19 In addition, to increase confidence in the long-term stability of the site, the licensee should focus
20 on: (1) using natural analogs to better understand and evaluate long-term degradation
21 processes, including both spatial heterogeneity and temporal trajectories of change; (2)
22 designing covers that mimic the favorable attributes of selected natural analogs; (3) evaluating
23 effects of soil development and ecological change; (4) evaluating effects of waste subsidence
24 on long-term cover performance; and (5) predicting and incorporating landform changes in
25 cover and disposal cell designs (NRC, 2011b). In addition, the performance of an ET cover can
26 be particularly sensitive to temporal and spatial variability in precipitation and other processes.

27 **5.3.3 Monitoring of Engineered Barriers**

28
29 Most waste containment facilities require monitoring to verify performance and/or support
30 predictive modeling (NAS/NRC, 2007). Environmental monitoring of a LLW disposal facility is
31 required for the duration of the institutional control period. The design of monitoring systems for
32 engineered barriers has proven difficult as a result of technological challenges and complex
33 goals; however, progress is being made. Observing the effects of degradation processes is
34 critical to understanding long-term performance. Performance monitoring of engineered surface
35 covers provides a licensee confidence that the cover is functioning as predicted in the
36 performance assessment, intruder assessment, or site stability assessment.
37

38 Monitoring of engineered covers generally is conducted at two levels: direct non-destructive
39 performance monitoring, and direct or indirect interpretive monitoring. Performance monitoring
40 consists of directly and continuously monitoring the primary performance variable (e.g., the flux
41 of water through a cover) using an in-situ device. Interpretative monitoring consists of
42 measuring secondary variables (e.g., water content) related to the primary performance variable
43 that can be used to understand or interpret data obtained from primary performance monitoring
44 (NRC, 2011a). Interpretive monitoring can be conducted directly using embedded sensors or
45 indirectly using remote sensing methods such as ground penetrating radar or airborne radar
46 systems. Water content and temperature are the two most commonly measured secondary
47 variables employed for interpretive monitoring. Interpretive monitoring currently is conducted

1 almost exclusively using direct methods. However, indirect remote sensing methods likely will
2 become more important in the future, especially for long-term monitoring from remote locations
3 (NRC, 2011a).

4
5 During the period of institutional controls, licensees must perform environmental monitoring to
6 ensure continued satisfactory disposal system performance and to develop confidence that the
7 observed performance is likely to persist after the institutional control period. Licensees should
8 also perform physical surveillance to restrict access to the site and minor custodial activities
9 during the institutional control period. Short-term performance of the disposal site can be
10 physically monitored with various types of onsite instrumentation or by remote sensing.
11 Licensees can use monitoring to: detect any early significant releases of contaminants, and to
12 verify the validity of assumptions made and the accuracy of the results of predictive modeling,
13 thereby, reducing uncertainty. Though not required, the NRC staff strongly recommends that
14 licensees conduct interpretive monitoring because it can provide observations of performance
15 problems that are a precursor to releases of radioactivity into the environment.

16
17 Licensees should include assumptions, parameters, and features that have a large influence on
18 the disposal facility performance and have relatively large uncertainties as an important part of a
19 monitoring plan. For example, monitoring plant processes or more generally ecological
20 processes, can add greatly to understanding cover stability and performance. Even carefully
21 designed cover systems begin a process of change immediately following construction. These
22 changes can affect containment system performance both directly and indirectly, and should be
23 monitored. Additional information gained through various sources can reduce uncertainties and
24 support previous predictive modeling. Monitoring is considered important in obtaining
25 confidence that barrier components are performing as intended and is an important tool in
26 detecting early signs of degrading stability of a disposal system. Because of increased
27 understanding of potential shortcomings with engineered surface barriers, monitoring of
28 engineered systems is being recognized as a powerful tool that has the potential to yield
29 valuable data. A well-conceived monitoring system for engineered surface barriers would
30 provide information to assess barrier performance including degradation.

31
32 Airborne and satellite-based remote monitoring techniques are able to efficiently monitor
33 particular aspects of the engineered surface covers. For example, remote sensing may detect
34 vegetative change that is dependent on characteristics of water flow. Linear features of heavier
35 vegetation may be indicative of cracks or other structural features allowing increased contact of
36 water with the waste and may be indirect signs that the overall stability of a barrier may be
37 decreasing. Sensor development has rapidly advanced so that sensors are becoming not only
38 quicker, more reliable, and longer lasting, but also smaller, more automated, wireless, and more
39 sophisticated. Licensees can obtain changes in vegetation, soil water content and temperature
40 through multispectral imaging. Ground penetrating radar, LIDAR (or Light Detection and
41 Ranging technology), and other remote sensing techniques may detect stabilization problems at
42 the very early stages due to its high resolution output (NAS/NRC, 2007). Licensees may
43 someday be able to place automated sensors throughout the different components of the cover
44 to monitor those features and processes demonstrated to be significant.

45
46 Licensees should not use monitoring as a substitute for the development of an adequate
47 performance database prior to implementing their system, but rather to support the previous
48 determination of adequacy considering uncertainty. When there is uncertainty associated with

1 the waste disposal system, monitoring can maintain confidence in the performance
2 demonstration.

3
4 Monitoring and modeling activities are complementary to one another. Modeling can serve to
5 focus monitoring efforts by identifying key processes and parameters or disconnects between
6 field observations and model results. Similarly, the results of monitoring provide feedback to
7 refine models and improve the understanding of the system. Licensees should design their
8 monitoring systems to understand processes and events and identify early indicators of
9 performance problems.

10
11

6.0 PROTECTIVE ASSURANCE PERIOD ANALYSES

10 CFR 61.41(b) requires that:

Concentrations of radioactive material that may be released to the general environment in groundwater, surface water, air, soil, plants, or animals shall be minimized during the protective assurance period. The annual dose, established on the license, shall be below 5 mSv (500 mrem) or a level that is supported as reasonably achievable based on technological and economic considerations in the information submitted for review and approval by the Commission. Compliance with this paragraph must be demonstrated through analyses that meet the requirements specified in 10 CFR 61.13(a).

10 CFR 61.42(b) requires that:

Design, operation, and closure of the land disposal facility shall minimize exposures to any inadvertent intruder into the disposal site at any time during the protective assurance period. The annual dose, established on the license, shall be below 5 mSv (500 mrem) or a level that is supported as reasonably achievable based on technological and economic considerations in the information submitted for review and approval by the Commission. Compliance with this paragraph must be demonstrated through analyses that meet the requirements specified in 10 CFR 61.13(b).

The primary purpose of the protective assurance period analyses is to provide information that demonstrates that releases of radioactivity from a LLW disposal facility are minimized during the protective assurance period. Minimization is the reduction of doses to as low as reasonably practical with technical and economic factors taken into consideration. The protective assurance period is the period from the end of the compliance period through 10,000 years following closure of the site. This section provides guidance on developing the technical analyses for the protective assurance period.

The requirements for the protective assurance period differ from the compliance period in two respects. First, the requirement for 10 CFR 61.41(b) and 10 CFR 61.42(b) is minimization. As explained later in this section, minimization should not be interpreted to mean that zero release or zero risk can be achieved. Few activities are without risk; there must be a balance between the health and safety measures that are introduced to control risk and the costs arising or benefits forgone when these health and safety measures are introduced. Depending on the particular waste and the technical challenges associated with its disposal, the end point of the minimization process may correspond to different levels of risk or dose. Second, a target to compare the minimization against is provided in the regulation (i.e., 5 mSv (500 mrem)); however, other targets may be supported if they are reasonably achievable based on technological and economic considerations. The process of minimization typically involves a comparison of alternatives and could involve cost-benefit analysis. Generally, a preferred option is compared to various alternatives to justify that the preferred option minimizes impacts in a technically and economically practical manner. There are many different technical and programmatic options (e.g., an enhanced wasteform) that can be used to control risk. If impractical, not all of the combinations of these options need to be evaluated; however, each of the main technical options should be evaluated. Section 6.1 provides guidance on developing

1 the scope of the analyses for the protective assurance period. Section 6.2 discusses the
2 conceptual framework for the analyses, presents different types of analyses that may be
3 considered by licensees, as well as the NRC staff's recommended approach for applying long-
4 term discounting to LLW disposal. The minimization process and associated metrics are also
5 described.

6 **6.1 Scope of the Protective Assurance Period Analyses**

7
8 Protective assurance analyses are an extension of the technical analyses used to evaluate
9 disposal system performance during the compliance period. The results of the performance
10 assessment, intruder assessment, and site stability assessment provide the technical basis to
11 demonstrate that impacts to the general population and inadvertent intruders have been
12 minimized.

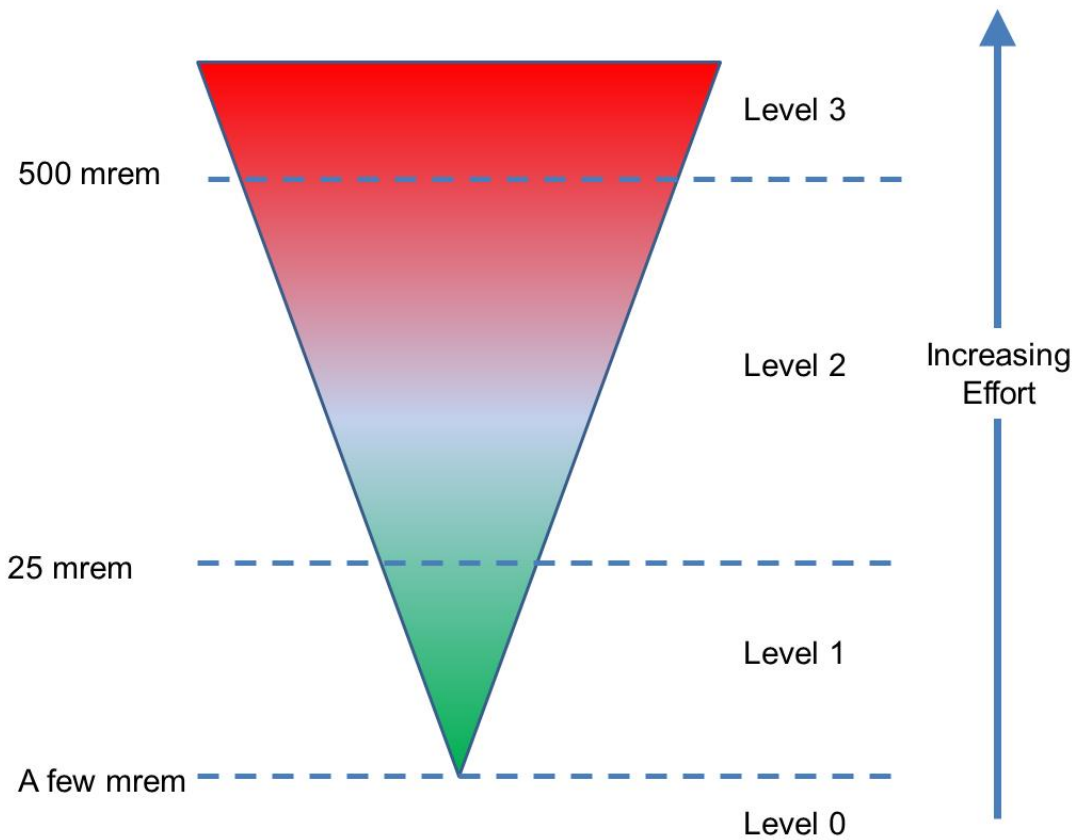
13
14 The assumptions, data, and models used to develop the compliance period technical analyses
15 will be sufficient for the protective assurance period analyses unless changes are necessary to
16 address the uncertainties associated with the longer timeframes. If scientific information is
17 available, or can be developed in a cost-effective manner, then the compliance period
18 assessments should be enhanced or modified. The FEPs that were represented in the
19 compliance period analyses will generally apply to the protective assurance period, although the
20 frequency and magnitude may vary temporally. Section 2.5 provides guidance on developing
21 the scope of the technical analyses.

22 **6.2 Framework for the Protective Assurance Period Analyses**

23
24 The analyses for the protective assurance period will be similar to the technical analyses for the
25 compliance period. The primary difference will be in the metrics used to evaluate the results of
26 the analyses. Figure 6-1 provides the framework for the minimization process used for the
27 protective assurance analyses applied to 10 CFR 61.41(b). The recommended approach is to
28 treat the minimization process similar to an optimization problem, using the doses estimated
29 from the technical analyses (e.g., performance assessment, intruder assessment) as the
30 objective function. The requirements for protective assurance analyses apply to both
31 10 CFR 61.41(b) and 10 CFR 61.42(b), however, the process for the latter should be simpler.

32
33 Figure 6-1 depicts levels that licensees should consider and regulators should evaluate that
34 distinguish different degrees of effort and types of analyses that may be performed for the
35 minimization process. A graded approach to the protective assurance period analyses is
36 recommended. Licensees should consider uncertainty in the protective assurance analyses.
37 The absence of the evidence of risk does not prove that risks are not present. For example, a
38 licensee may claim that no releases from their LLW disposal facility have been observed,
39 however, they may not have installed any monitoring wells that would be able to detect such
40 releases (i.e., the absence of the evidence of risk). This claim would have significantly different
41 meaning than the assertion by a licensee that releases from their LLW disposal facility have not
42 been observed because monitoring wells were installed and samples were tested (i.e., evidence
43 that risks are not present).

44



1
2
3 **Figure 6-1 Analyses Framework for the Minimization Process for the Protective**
4 **Assurance Period Analyses Applied to 10 CFR 61.41(b)**

5
6 Proposed waste disposal is different from a remediation or clean-up activity in that waste
7 disposal is a potential *future* action that could result in future harm to the public, whereas a
8 remediation activity involves evaluating what should be done to remedy a *previous* action that
9 could result in future harm to the public. The operator of a waste disposal facility can set waste
10 concentration and inventory limits that will control future doses to essentially any level desirable
11 if the associated technical analysis is of high quality and is reasonably accurate. Inventory limits
12 are quantity- or concentration-based limits on the amount of radioactive isotopes suitable for
13 disposal at a particular location. Inventory limits can play a key role in managing risk.

14
15 Uncertainty in projected doses is an important factor for licensees and regulators to consider
16 when determining the appropriate target to use when evaluating the minimization process. If
17 there are significant uncertainties, then the minimization process should be biased towards
18 more conservative levels (i.e., more effort to minimize). The levels a licensee may consider for
19 minimization under 10 CFR 61.41(b) include:

20
21 Level 0: At hundredths of mSv/yr (a few mrem/yr and below), design, process, waste
22 acceptance, or other changes are generally not warranted unless they result in a

1 cost savings without increasing worker exposures. Therefore, analyses of
2 alternatives are not necessary for Level 0.

3
4 Level 1: Above a few mrem/yr and up to the compliance period dose limit of 0.25 mSv/yr
5 (25 mrem/yr), changes to design, process, waste acceptance or other areas may
6 be warranted if they can be justified based on technological and economic
7 considerations. The analyses of alternatives may be qualitative or quantitative.
8 Quantitative analyses are preferred. Inventory limits may be used to limit doses
9 if there is uncertainty that the doses are Level 1 or that they may be higher. A
10 licensee may also propose and implement inventory limits for purposes other
11 than the quantitative dose assessment (e.g., to simplify waste handling and
12 management).

13
14 Level 2: Above 0.25 mSv/yr (25 mrem/yr) and up to 5 mSv/yr (500 mrem/yr), changes to
15 design, process, waste acceptance or other areas may be warranted unless they
16 are shown to be impractical based on technological and economic
17 considerations. The analyses of alternatives should be quantitative to the extent
18 practical. Inventory limits should be used to maintain projected future doses
19 below 5 mSv/yr (500 mrem/yr) and those inventory limits should be reflected in
20 the associated waste acceptance criteria.

21
22 Level 3: Above 5 mSv/yr (500 mrem/yr), changes to design, process, waste acceptance,
23 or other areas are expected of the licensee unless they are shown to be
24 impractical based on technological and economic considerations. For example,
25 changes to the wasteform or geochemistry of the disposal cells may significantly
26 reduce projected future doses. The analyses of alternatives should be
27 quantitative, and include a rationale for why the annual dose cannot be reduced
28 to 5 mSv/yr (500 mrem/yr) based on technological and economic considerations.
29 The analyses of alternatives should consider why inventory limits cannot be
30 established. The licensee and regulator should consider if an alternative facility
31 could receive the waste and maintain doses below 5 mSv/yr (500 mrem/yr).

32
33 For Level 3, the analyses of alternatives should be broader and more comprehensive compared
34 to the other levels. One method that is irrefutably capable of reducing risk is to establish
35 concentration- or quantity-based inventory limits. Inventory limits may be used to account for
36 potential shortcomings in the engineered or natural components of a LLW disposal system. In
37 addition, if the results of the analyses demonstrate that doses for 10 CFR 61.41(b) are likely to
38 be above 5 mSv/yr (500 mrem/yr), the results may indicate that the proposed disposal facility
39 and disposal site are not suitable candidates for that type of waste. Alternative disposal
40 facilities may exist that can better manage the particular radiological hazard.

41
42 The minimization process for 10 CFR 61.42(b) is conceptually similar to 10 CFR 61.41(b) with
43 the exceptions that different levels and a simpler process can be used. A variety of factors
44 contribute to this recommendation. The inadvertent intruder is a hypothetical construct to
45 account for the uncertainty with respect to providing long-term control of a closed disposal site,
46 and intruder doses are usually driven by short-lived waste for most commercial LLW. In
47 addition, the dose limit for the intruders during the compliance period is significantly higher than
48 the limit found in 10 CFR 61.41(a). Finally, the long-term performance of engineered barriers to
49 inhibit intruder doses during the protective assurance period cannot be reliably assured. Each

1 of these factors contributes to making the minimization process for the intruders somewhat
2 different than for 10 CFR 61.41(b). Whereas there may be practical actions that can be taken to
3 minimize doses to a member of the public for 10 CFR 61.41(b), it is more challenging to identify
4 actions to minimize doses for a hypothetical intruder scenario. Because it is more difficult to
5 identify actions, a simpler approach is recommended for minimizing intruder doses. The
6 recommended approach for 10 CFR 61.42(b) is to minimize intruder doses below a 500
7 mrem/yr target (analogous to Level 1 above but with the corresponding equivalent threshold) or
8 to a level that can be justified based on technological and economic considerations.

9 **6.2.1 Types of Analyses**

10

11 A licensee has flexibility in the type of analyses to use for the protective assurance period. The
12 analyses should be tailored to the specific waste, disposal facility design, and the projected
13 future radiological doses. The suitability of particular analyses to support decision-making may
14 be impacted by projected uncertainty. If projected uncertainty is relatively large, it may not be
15 clear from the results of analyses which alternatives should be adopted and which can be
16 rejected. Therefore, the licensee should err on the side of evaluating more alternatives to
17 ensure defense-in-depth will be provided. In addition, a larger set of alternatives may be
18 considered because some of those alternatives may help to reduce uncertainty in the projected
19 performance.

20 **6.2.1.1 Alternatives Analyses**

21

22 The simplest form of analysis for the protective assurance period is for a licensee to compare
23 alternatives. This section provides guidance on:

24

25 What alternatives should be considered by a licensee?

26 How much detail should be included in the analyses?

27 Should combinations be evaluated by a licensee?

28

29 In general, in an alternatives analysis, a licensee will have a base case or preferred alternative
30 with an associated projected impact (i.e., dose). An alternatives analysis can be simpler than a
31 minimization or cost-benefit analysis because economic variables may be omitted. For the
32 alternatives analysis, the base case or preferred alternative should be the alternative that is
33 projected to result in the lowest dose or that calculates a dose comparable to the lowest result
34 given the uncertainty. If the preferred alternative dose is not comparable to the lowest dose,
35 then technological and economic practicality can be factored into the decision, as discussed in
36 Section 6.2.1.2.

37

38 Performance assessments may be deterministic or probabilistic, but regardless of the type of
39 analyses all performance assessments should consider uncertainties. The base case or
40 preferred alternative will usually have the lowest projected doses. However in some cases a
41 number of alternatives may be comparable when uncertainties in the projected doses are
42 considered. The projected uncertainties will be reflected in a range of estimated doses. If the
43 analysis is probabilistic, the appropriate metric to use is the peak-of-the-mean dose. Though
44 the peak-of-the-mean dose is a scalar output, it will have uncertainty associated with the
45 estimated value. The uncertainty in the estimates of the peak-of-the-mean doses for different
46 alternatives may overlap. Alternatively, plots of other percentiles of projected doses can be
47 compared when selecting an alternative. When uncertainty causes the results to overlap the

1 “lowest” result may not be unambiguously identified, and therefore other considerations may be
2 taken into consideration when selecting the preferred alternative or base case.

3
4 The main variables to consider as alternatives generally include:

- 5
- 6 • Design (e.g., different engineered barriers),
- 7 • Processing (e.g., waste emplacement and configuration), and
- 8 • Waste acceptance (e.g., waste types, waste streams, waste characteristics).
- 9

10 The framework for the protective assurance period analyses provides for a risk-informed
11 approach based on the projected future doses. For projected future doses of a few mrem per
12 year and less (Level 0), formal evaluation of alternatives is not necessary. Because the doses
13 are low, essentially the case for minimization has already been established by the licensee in
14 the base case or preferred alternative. An exception would be if the projected dose is low but
15 the uncertainty is high. In this case, it may be reasonable to evaluate alternatives to the base
16 case to see if the uncertainty can be reduced or managed. It should be noted that reduction in
17 uncertainty may not result in a reduction of risk; rather the risks may be better understood.

18
19 For projected future doses greater than a few mrem per year and up to 0.25 milliSieverts per
20 year (25 mrem per year) (Level 1), an evaluation of alternatives is recommended. However,
21 that evaluation should be focused on first-order effects of the main variables (e.g., design,
22 processing, waste acceptance). A large number of alternatives do not need to be considered;
23 generally less than ten alternatives should suffice. The analyses may be qualitative, although
24 quantitative analyses are preferred. The experience base considered for design and process
25 changes should include domestic experience, though licensees may also consider international
26 experience.

27
28 For projected future doses greater than 0.25 mSv/yr (25 mrem/yr) and up to 5 mSv/yr (500
29 mrem/yr) (Level 2), an evaluation of alternatives is recommended. Changes to design, process,
30 waste acceptance or other areas may be warranted unless their adoption cannot be justified
31 based on technological and economic considerations. The alternatives analysis should be
32 quantitative to the extent practical. The experience base considered for design and process
33 changes should focus on domestic experience but may also include international experience.
34 The number of alternatives considered should be complete without being exhaustive. For
35 example, the licensee should be able to use the results of the performance assessment to
36 identify those features of the design that are most important to limiting releases, or that provide
37 defense-in-depth. Alternatives analyses should include variants of the key design features.
38 Design alternatives should include those related to the hydrology, geochemistry, site stability,
39 wasteforms, or other significant characteristics. Depending of the projected doses, a licensee
40 may wish to consider combinations of alternatives, as the projected responses of performance
41 assessment models is not always linear and complex responses can occur. Alternatives may
42 be rejected if they are not technologically or economically practical irrespective of the benefits to
43 system performance.

44
45 A primary difference between the analyses for Level 2 and Level 1 is the consideration of
46 inventory limits to maintain projected future doses to a prescribed level.¹ Inventory limits should

¹ This section is focused on 10 CFR 61.41(b). As noted previously, the approach recommended for 10 CFR 61.42(b) is simpler.

1 be used to maintain projected future doses below 5 mSv (500 mrem) and those inventory limits
2 should be reflected in the associated waste acceptance criteria. For waste disposal, inventory
3 limits can be derived that correspond to different levels of dose to a member of the public. In
4 many cases, it may be practical for a licensee to set inventory limits that correspond to a fraction
5 of the 5 mSv (500 mrem/yr) target. A licensee should consider alternative inventory limits in the
6 minimization process for Level 2.

7
8 For projected future doses to a member of the public greater than 5 mSv/yr (500 mrem/yr)
9 (Level 3), evaluation of alternatives is necessary. The licensee is expected to make changes to
10 the design, process, waste acceptance or other areas unless changes cannot be justified based
11 on technological and economic considerations. The experience base considered should include
12 domestic and international experience as well as emerging technologies that may become
13 viable in the near term. The number of alternatives the licensee considers should be complete
14 and include the identification of relevant combinations of alternatives that may have significantly
15 increased performance. Design features that act in combination may enhance performance or
16 provide defense-in-depth. The analyses of alternatives performed by a licensee should be
17 quantitative, and include a rationale for why the annual dose cannot be reduced to 5 mSv (500
18 mrem) or lower based on technological and economic considerations. The licensee should
19 justify in the alternatives analysis why inventory limits cannot be established to lower the
20 projected future dose. The presence of previous disposals that could result in future doses
21 greater than 5 mSv (500 mrem) is not a sufficient basis for allowing future LLW disposals to
22 result in doses of that magnitude. Previous and future disposals may be managed separately
23 such that the impacts do not overlap, especially with respect to demonstration of compliance
24 with 10 CFR 61.42(b). The licensee should provide the regulator with a strong basis for why the
25 waste should be accepted at their facility, despite the higher projected dose, as opposed to
26 being disposed at an alternate LLW disposal facility. The regulator should consider, through
27 consultation with peers at other regulatory agencies, if an alternative facility could receive the
28 waste and maintain doses below 5 mSv (500 mrem). The alternative facilities considered
29 should be limited to existing facilities or proposed facilities for which technical analyses are
30 available. In most cases existing facilities will have developed inventory limits for a large
31 number of isotopes. Therefore, it should be easy to determine the quantity of a particular new
32 waste stream that an existing facility could suitably dispose.

33 **6.2.1.2** *Minimization Analysis*

34
35 Whereas the alternatives analysis discussed in the previous section examines different options
36 based on projected annual doses, the minimization analysis may also include economic
37 considerations. This section provides guidance for licensees completing analyses and for
38 regulators reviewing analyses on:

- 39 • Long-term discounting,
- 40 • Metrics to use for minimization analysis, and
- 41 • Consideration of uncertainty.

42
43 A challenge with minimizing the long-term impacts from LLW disposal is that the costs may be
44 incurred in the near term, whereas the impacts or benefits, such as averted doses, may not be
45 observed until hundreds or thousands of years in the future. In addition, the size of the group
46 that may be exposed in the future, especially the distant future, is difficult to estimate with a high
47 degree of confidence due to the complexity of estimating future land use and demographic

1 changes. There is no clear consensus in the technical literature with respect to discounting very
2 long-term impacts in order to perform cost-benefit analysis or other similar types of analyses.
3 Discounting has been applied by some researchers, though the timeframes are generally limited
4 to a few hundred years. Some researchers have inferred effective discount rates from financial
5 data (e.g., long-term lease data) and have concluded that they are likely to be very low (e.g.,
6 fractions of a percent) with respect to financial decisions (Giglio et al., 2013). The issue of *long-*
7 *term* discounting combines technical and philosophical components; staff favors a pragmatic
8 solution over theoretical rigor.

9
10 The NRCs recommended approach to discounting applied to regulatory analysis development
11 for backfitting can be found in NUREG/BR-0058, Rev. 4 (NRC, 2004d).² A distinction is made
12 between shorter-term problems (e.g., reactor licensing) and problems involving the long-term
13 and potential intergenerational considerations (e.g., decommissioning or waste disposal).

14 The approach recommended here (e.g., long time horizons) has four components:

- 15 1. Discount costs of alternatives over the operational life,
- 16 2. Do not discount long-term future averted doses (i.e., benefits), and
- 17 3. Evaluate alternatives based on a) the normalized effectiveness of the alternative and b)
18 the absolute level of the risk involved.
- 19 4. Consider uncertainty and sensitivity in the assumptions.
- 20
- 21
- 22

23 Discounting of costs to compare design alternatives is a well-established method used in
24 engineering economics. Consideration of the time value of money is central to most
25 engineering projects. For example, to compare two alternatives one that involves a capital
26 expenditure today with one that involves an expenditure that will occur *n* years in the future, the
27 present value of the future expenditure is estimated with:
28

$$PV = FV \frac{1}{(1 + r)^n}$$

29 where *r* is the annual discount rate.
30
31

² The NRC staff's recommended approach to discounting for shorter-term problems was initially reflected in NUREG-1757, Appendix N for application to ALARA analyses in decommissioning (up to a 1,000 year timeframe). However, portions of that appendix, including the recommendations for discounting, were later withdrawn (NRC, 2007d). NUREG/BR-0058, Rev 4 discusses the issue: For certain regulatory actions, such as those involving decommissioning and waste disposal issues, the regulatory analysis may have to consider consequences that can occur over hundreds, or even thousands, of years. The Office of Management and Budget (OMB) recognizes that special considerations arise when comparing benefits and costs across generations. Under these circumstances, OMB continues to see value in applying discount rates of 3 and 7 percent. However, ethical and technical arguments can also support the use of lower discount rates. Thus, if a rule will have important intergenerational consequences, one should consider supplementing the analysis with an explicit discussion of the intergenerational concerns such as how future generations will be affected by the regulatory decision. Additionally, supplemental information could include a presentation of the values and impacts at the time in which they are incurred with no present worth conversion. In this case, no calculation of the resulting net value or value-impact ratio should be made. Also, one should consider a sensitivity analysis using a lower, but positive discount rate. Finally, as a general principle, sensitivity or uncertainty analysis, or both, should be performed.

1 On the other hand, discounting of benefits (e.g., averted doses) is open to considerable debate.
2 Over very long timeframes, the mathematics of discounting results in the conclusion that the
3 current generation should not invest any resources to mitigate impacts that occur to distant
4 future generations. The NRC staff's recommendation not to discount long-term, future averted
5 doses is based on the position that the current generation is responsible for the long-term
6 impacts from its LLW disposal decisions and that the solution for these impacts should not be
7 deferred to future generations.

8
9 In order to compare alternatives, the recommended approach is 1) to normalize the cost of the
10 alternative to what is considered to be an appropriate amount (cost) to protect the current
11 generation (e.g., the base cost of the facility), and 2) to scale the normalized result based on
12 risk. Higher risk should result in a higher threshold to reject an alternative, whereas at very low
13 risk, all alternatives should be rejected. The use of the term 'risk' here is referring to the
14 projected doses to a member of the public or an inadvertent intruder. A broader interpretation of
15 risk for the risk-based discounting process may unnecessarily complicate the decision-making
16 process. However, licensees may choose to consider the balance between future risk from
17 disposed waste and present risk to workers or the public. For example, a wasteform with much
18 higher durability could have much lower waste loading, resulting in a transfer of risk but not a
19 significant reduction (e.g., from disposal to transportation). The metric the NRC staff developed
20 is to compare the proportional increase in cost for the alternative relative to the base cost of the
21 facility (e.g., the appropriate cost to protect the current generation) against the fractional change
22 in long-term impacts. The overall result is then conditional on the absolute level of the risk as
23 presented in Figure 6-1. This is explained in more detail with an example later in this section.

24 25 Long-term Discounting:

26 The NRC has developed a policy to inform regulatory decision-making with respect to
27 rulemaking that is subject to NRC's backfit requirements. A \$2,000 per person-rem conversion
28 factor has been applied to inform regulatory decisions for fuel cycle facilities (NUREG-1530) and
29 evaluate potential new regulatory requirements (NRC, 1995d; NRC, 2004d). The conversion
30 factor is also used in regulatory applications, such as in ALARA analyses, to provide a monetary
31 valuation to collective dose. A number of criticisms have been expressed about the use of
32 collective dose (NCRP, 1995). Though some have found collective dose still has value in
33 comparing alternatives (Brock and Sherbini, 2012). The dollar per person-rem conversion factor
34 attempts to capture the dollar value of the health detriment resulting from radiation exposure.
35 Health detriments (e.g., excess cancer fatalities) are linked to radiation exposure through
36 conversion factors (e.g., 0.05/Sv).

37
38 In NUREG-1530, the NRC staff evaluated different methods to value a statistical life to develop
39 a dollar per person-rem factor (NRC, 1995d). One method looked at values implied by
40 government expenditures for many different programs designed to protect human life. The
41 values in 1990 dollars ranged from \$12,000 per statistical life for scoliosis and neuromuscular
42 disease to \$85,000 for regulatory and warning signs. The implied value to limit exposure in the
43 defense HLW program was \$490 million per statistical life. The primary driver of the large range
44 of results was the differences in the amount spent on each program, not in the methods to
45 calculate the statistical deaths. The NRC staff's evaluation resulted in a large range of values of
46 expenditures per statistical life and the values for nuclear issues, especially nuclear waste
47 issues, tended to be at the very high end of the range.
48

1 The range of positions taken on long-term discounting is extremely large (Farber and
2 Hemmersbaugh, 1993). There are a variety of considerations discussed in the technical
3 literature that the NRC staff considered when developing this guidance. These include but are
4 not limited to:

- 5 • The long-term doses from LLW disposal could be relatively small but persist for a very
6 long period of time. Without discounting, the cumulative effect could be very large if the
7 exposed population is large. However, the incremental increase in risk to any individual
8 would be very small, perhaps below the threshold where individuals take action or
9 otherwise modify their behaviors.
- 10 • Because of the timeframes involved, if a licensee were to use discounting to estimate
11 the present worth of benefits (e.g., averted doses), even at very low discount rates, the
12 licensee may conclude that no amount should be spent today to mitigate long-term
13 radiological risks (i.e., beyond a few hundred years).
- 14 • Society incurs the cost of LLW disposal regulation long before the benefits of doses
15 averted; compound discounting has a greater impact in the calculation of the present
16 value of benefits than on the costs because the benefits occur over much longer
17 timeframes.³
- 18 • Most studies of discounting are focused on the impacts within a generation and not on
19 the impacts to later generations. Studies that have looked at longer timeframes have
20 generally been limited to around a hundred years because there are not many longer
21 term problems.
- 22 • The NRC staff acknowledges that discounting is based on unstated economic
23 assumptions that may not be valid over very long timeframes (NRC, 1982b).
- 24 • Temporal volatility in discount rates can increase future valuations significantly
25 compared to assuming that rates are constant (Newell and Pizer, 2003).

26 Consistent with guidance provided in NUREG-1854 (NRC, 2007a), future long-term doses
27 should not be discounted with time to present day values in order to compare alternatives.⁴ As
28 discussed below, the recommended approach for a licensee to use is to compare the long-term
29 costs and reductions in dose to the compliance period costs and effectiveness of the design
30 while scaling the result with the magnitude of the projected long-term impacts. In other words,
31 even for a large reduction in long-term doses if the baseline long-term doses are small, the
32 resource expenditure is likely not warranted. This approach could be described as a normalized
33 utility-based approach with a floor threshold. The recommended approach is based on

³ Although a present benefit from disposal would be that the public is not exposed to radiation if the waste is disposed compared to a scenario if the waste is not disposed and control is lost.

⁴ Some stakeholders have referred to Appendix N of NUREG-1757 as providing guidance on the topic of long-term discount rates. However, relevant portions of Appendix N were withdrawn after issuance and are yet to be revised. This guidance refers to NUREG/BR-0058, Rev. 4, "Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission" (NRC, 2004d). Section 4.3.5 of NUREG/BR-0058 indicates that for certain regulatory actions, such as those involving decommissioning and waste disposal, special considerations arise when considering benefits and costs across generations. Section 4.3.5 indicates that the analysis should be supplemented with an explicit discussion of intergenerational concerns. This could be done by performing the analysis based on costs and impacts at the time they are incurred, with no present worth conversion, or by performing a sensitivity analysis using lower discount rates.

1 individual doses, thus avoiding the issues noted above with use of collective dose and
2 cumulative impacts.

3
4 The recommended approach is to estimate the cost of the alternatives represented by current
5 net present value (NPV) by applying discounting over the projected operational period of the
6 facility. A range of discount rates should be considered, such as in the range of 1 to 7 percent,
7 but biased towards the long-term trend values. Though long periods of deflationary rates have
8 not been frequent historically, the licensee could consider the sensitivity of the NPV calculations
9 to a deflationary period or periods. Sensitivity of the NPVs to the uncertainty in discount rates
10 should be examined. Considering the uncertainty, a licensee should be biased towards
11 conservatism (i.e., select alternatives that provide a greater reduction in risk). After the
12 operational period and preparation for closure, the site operator is not expected to be
13 performing significant activities at the disposal facility; therefore, discounting should not apply
14 after the operational period.

15 Metrics to Use for Minimization Analysis:

16 The performance metrics a licensee must apply to the assessment of long-term releases during
17 the protective assurance period is to minimize releases (10 CFR 61.41(b)) and to minimize
18 exposures to any inadvertent intruder (10 CFR 61.42(b)). In addition, the licensee must
19 demonstrate stability of the disposal site after closure (10 CFR 61.44). A target to compare this
20 minimization against is provided in the regulation (i.e., 5 mSv (500 mrem), or to a level that is
21 supported as reasonably achievable based on technological and economic considerations).
22 The metrics afford flexibility to a licensee to consider socioeconomic factors when assessing the
23 long-term protection of public health and safety.

24
25 These requirements to minimize releases and exposures are intended to be conceptually similar
26 to aspects of the ALARA requirement⁵ found in 10 CFR Part 20, which includes the use of
27 optimization, feasibility analyses, and traditional cost-benefit analyses. The 5 mSv (500 mrem)
28 value provided in the regulation is a target or dose goal to use in the minimization process. It is
29 not identical to a dose limit. In most cases, the NRC staff expects that the minimization process
30 will produce a design that is projected to result in doses to a member of the public much lower
31 than the target value. The minimization analysis is conceptually similar to ALARA, but it is not
32 identical.

33
34 Because of the problems associated with discounting over long timeframes, the NRC staff
35 recommends that licensees follow the process given below to implement the minimization
36 process. Other processes may also be suitable and regulators may evaluate any other
37 processes on a case-by-case basis. Based on the results of their minimization analyses,
38 licensees may elect to adopt alternatives that are more protective.

39
40 The analyses should be based on best estimates and uncertainties. Uncertainty may impact
41 whether an alternative should be adopted or not. If the uncertainties are low, and confidence in
42 the decision to eliminate an alternative is high, then it is practical to not adopt the alternative. If

⁵ ALARA is defined as "making every reasonable effort to maintain exposures to radiation as far below the dose limits in this part as is practical consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to the state of technology, the economics of improvement in relation to benefits to public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest." See 10 CFR 20.1003.

1 the uncertainties in the estimates are comparatively higher, and confidence in a decision to
 2 eliminate an alternative is low, then caution is warranted and the alternative should be adopted.
 3 If the uncertainties are prohibitively large (see Section 6.2.1.4), then inventory limits may be
 4 necessary to mitigate those uncertainties or disposal of certain waste isotopes may not be
 5 appropriate. Because of the different types of uncertainties and their magnitudes in relation to
 6 the decision metrics, many different approaches to factoring uncertainty into the minimization
 7 process may be appropriate and should be evaluated on a case-by-case basis. A licensee is
 8 not required to, but may consider, performing the minimization process calculations
 9 probabilistically. Uncertainty in the doses, net present values, design effectiveness, and level
 10 scaling factors could be included resulting in probability distributions of the outputs.

11 Minimization Process:

12 The following variables are defined:

13 "D_x" is a dose for scenario or alternative x in units of mrem/yr

14 "NPV_x" is the net present value for scenario or alternative x in units of \$

15 "Eff_x" is the effectiveness of the scenario or alternative x in units of mrem/yr-\$

16 **D_{base}** = Peak dose from the base design within the protective assurance period

17 **D_{natural}** = Peak dose without the base design within the protective assurance period (natural
 18 barrier capabilities only)

19 **D_{natural-int}** = Peak dose to the intruder without the base design during the protective assurance
 20 period

21 **D_{base-int}** = Peak dose to the intruder with the base design during the protective assurance period

22 **NPV_{base}** = NPV of the base design (\$)

23 **Eff_{base}** = the effectiveness of the base design within 10,000 years (dose/\$)

24 **D_{alti}** = Peak dose from alternative i during the protective assurance period

25 **NPV_{alti}** = NPV of alternative i (\$)

26 **Eff_i** = the effectiveness of alternative i for the protective assurance period (dose/\$)

27 **Lf** = Level scaling factor⁶ (dimensionless)

28 **NER** = Normalized Effectiveness Ratio

29 For evaluation of minimization with respect to 10 CFR 61.41:

30 *For D_{base} < 25 mrem/year: Lf = 0*

31 *For D_{base} ≥ 25 mrem/year: Lf = 0.13 * (D_{Base})^{0.333}*

32 For evaluation of minimization with respect to 10 CFR 61.42:

33 *For D_{base-int} < 500 mrem/year: Lf = 0*

34 *For D_{base-int} ≥ 500 mrem/year: Lf = 0.13 * (D_{base-int})^{0.333}*

35 1) Calculate the effectiveness of the base design using:

$$36 \text{Eff}_{base} = \frac{D_{natural} - D_{base}}{NPV_{base}} \quad (6.1)$$

37 ⁶ Development of the expressions for the level scaling factors is discussed later in this section.

1 2) Calculate the effectiveness of the n protective assurance period alternatives
2 (for i = 1 to n) using:

$$3 \text{ } Eff_i = \frac{D_{base} - D_{alt_i}}{NPV_{alt_i}} \quad (6.2)$$

5 3) Compare the results with the expression:

$$7 \text{ } NER_i = \frac{DE_{Base}}{DE_i} > Lf \quad (6.3)$$

8 If NER_i is greater than Lf for all alternatives, then the alternatives are not viable (i.e.,
9 minimization has been achieved). Example 6.1 demonstrates the application of this approach.

10
11 The peak doses used in the minimization process analysis should be consistent with the type of
12 analyses performed for the performance and intruder assessments. For instance, if probabilistic
13 analysis is used the recommended metric is the peak-of-the-mean. Uncertainty in the
14 magnitude and timing of the peak doses should be considered, especially if deterministic
15 analyses are used.

16
17 Figure 6-2 provides a conceptual representation of the level scaling factor (Lf), which is used to
18 compare with the normalized effectiveness ratio (NER). The value of the constant and the
19 exponent in the following equation ($Lf = 0.13 * (D_{base}, D_{base-int}, D_{natural}, \text{ or } D_{natural-int})^{0.333}$)
20 were selected to ensure the following:

- 21 • At very low values of dose, no resources would be expended to further reduce the
22 doses,
- 23 • At a dose of 500 mrem during the protective assurance period, the effectiveness of an
24 alternative would be compared on an equal basis with the effectiveness of the base
25 design during the compliance period, and
- 26 • At doses greater than 500 mrem, more resources would be practical to apply to reduce
27 the potentially large impacts.

28 The use of the level scaling factor, Lf , is a risk-based discounting approach. Figure 6-3 provides
29 the various Lf values highlighted on a hypothetical performance assessment model output that
30 would be used to demonstrate minimization for 10 CFR 61.41(b).

31
32 The benefits of this approach are 1) strong base designs are encouraged (i.e., larger Eff_{base}),
33 2) costs are scaled with doses, 3) resources are not expended for reducing very low doses, and
34 4) transparency of costs and alternatives is provided to regulators and other stakeholders.

35 Summary points of the approach are:

- 36 • It is a benefit to maximize Eff_{base} . This can be done by implementing as effective a
37 design as possible in a cost-effective manner (i.e., maximize performance, minimize
38 cost).
- 39 • It is also a benefit to having a highly-effective natural system (i.e., high-performance
40 LLW disposal site), because the Lf is scaled with overall dose levels.
- 41 • It is a benefit to minimize D_{base} . Selecting a base design that performs well for the
42 protective assurance period will reduce the viability of alternatives.

Example 6.1: A license applicant has developed an application to dispose of commercial LLW at the Nerak Site. If approved, the waste will contain a mixture of short- and long-lived isotopes. The applicant performed analyses of their base case design and estimated the peak dose to be 5 mrem/yr within 1,000 years and 172 mrem/yr within 10,000 years. They then performed analyses of the waste in the disposal site without the benefit of the base design features (e.g., engineered cover, concrete vaults, and waste packages) and estimated the peak dose would be approximately 220 mrem/yr at 10,000 years. The applicant's estimates of costs and doses are based on the median results of probabilistic analyses. The applicant considered three alternatives to the design and evaluated the effectiveness of those alternatives in minimizing projected doses for the protective assurance period. The results of various analyses developed by the applicant are:

Description	Time (yr)	NPV Cost (\$)	Peak dose (mrem/yr)
Base case – compliance	1,000	10,000,000	5
Site effectiveness –	10,000	NA	220
Base case – protective assurance	8,437	30,000,000	172
Alternative 1 – improved wasteform	10,000	110,000,000*	15
Alternative 2 – improved cover	8,708	20,000,000*	137
Alternative 3 – chemical barrier	10,000	1,000,000*	69

* Increase in cost over the base case, NPV = net present value

$$Eff_{base} = \frac{(220 - 172)mrem/yr}{\$30,000,000} = 1.6E-6 \frac{mrem}{\$-yr}$$

$$Eff_1 = \frac{(172 - 15)mrem/yr}{\$110,000,000} = 1.42E-6 \frac{mrem}{\$-yr}$$

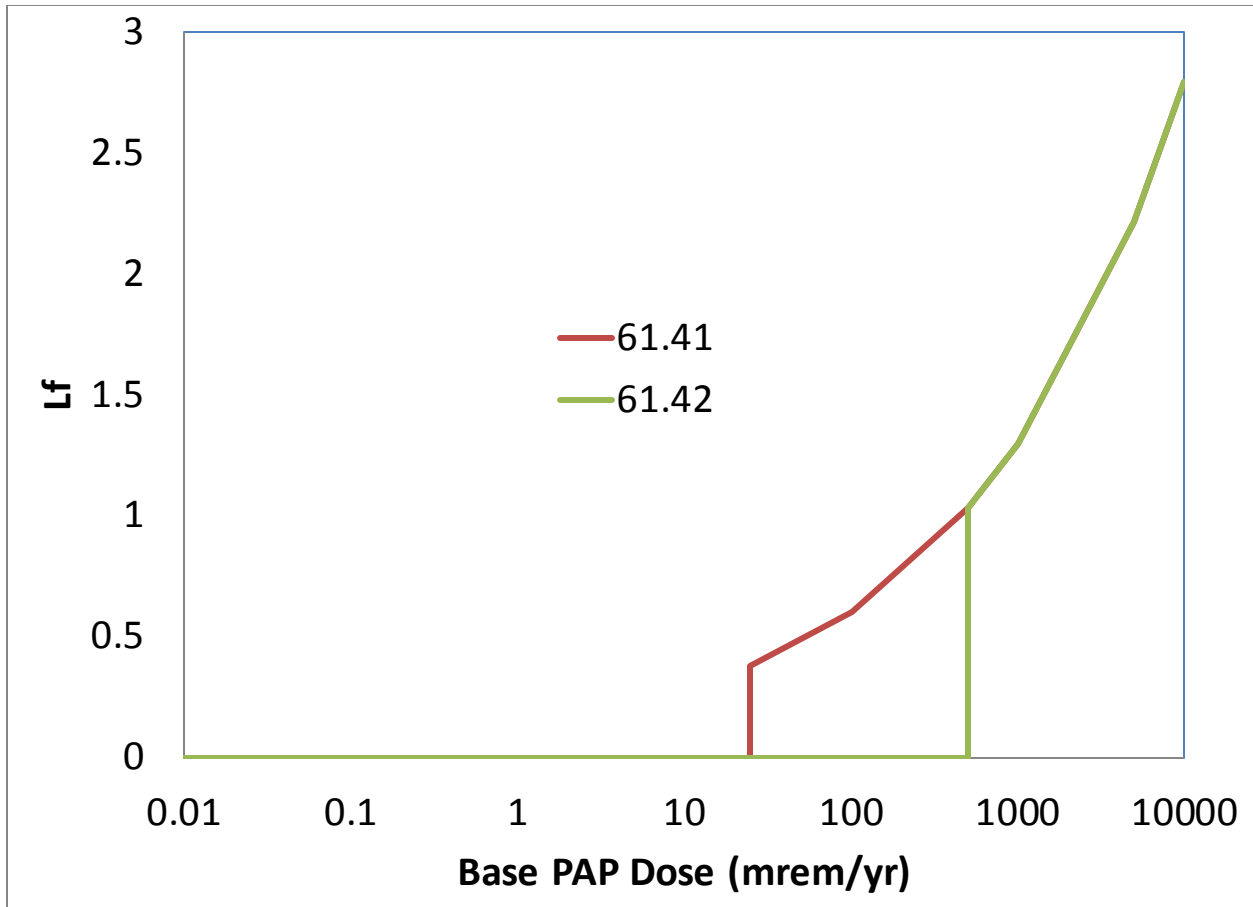
$$Eff_2 = \frac{(172 - 137)mrem/yr}{\$20,000,000} = 1.75E-6 \frac{mrem}{\$-yr}$$

$$Eff_3 = \frac{(172 - 69)mrem/yr}{\$1,000,000} = 1.03E-4 \frac{mrem}{\$-yr}$$

$$Lf = 0.13 * (172)^{0.333} = 0.72$$

$NER_1 = 1.13$, $NER_2 = 0.91$, and $NER_3 = 0.02$. Since NER_3 is less than the L_f , then the base design does not adequately minimize releases (in the case of releases to the general population). The exposures to inadvertent intruders would be evaluated with a similar approach using the pertinent information. The license applicant proposes in their application that a chemical barrier will be added to the base case design in order to minimize releases for the protective assurance period.

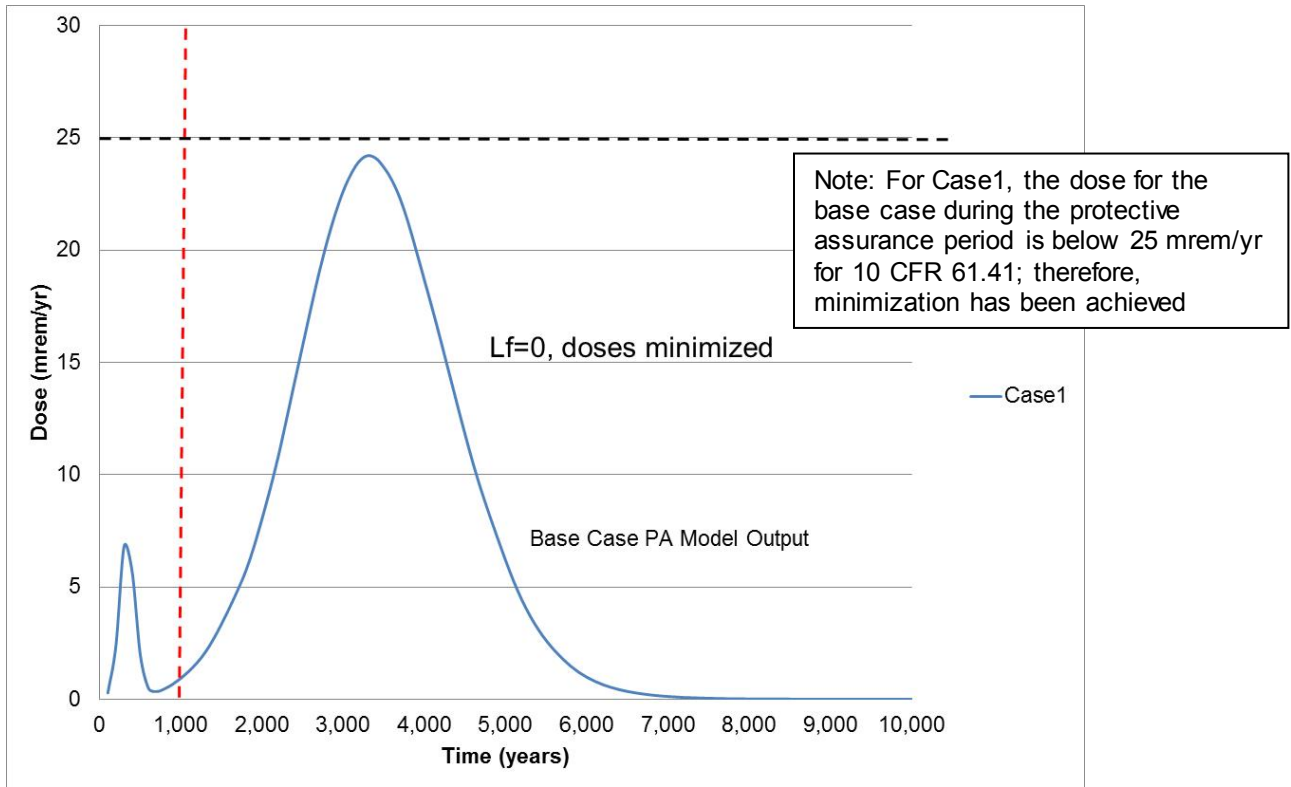
Conclusion: After examining the sensitivity of the results to the uncertainties, the regulator concludes that with the chemical barrier added (Alternative 3) the license applicant has demonstrated that releases would be minimized for the protective assurance period.



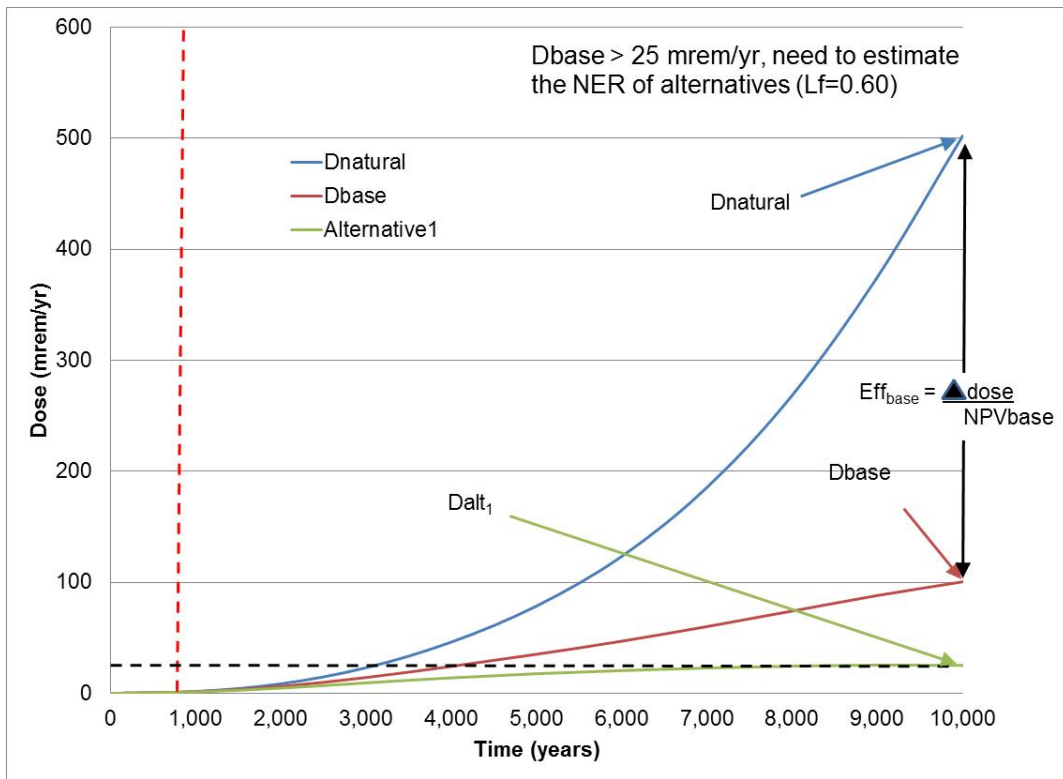
1
2 **Figure 6-2 Level Scaling Factors as a Function of the Base Case Dose in the**
3 **Protective Assurance Period (For 10 CFR 61.41 and 10 CFR 61.42)**

- 4
- 5 • By setting the *Lf* to 0 below a threshold, design alternatives will not be implemented, and
 - 6 therefore, costs will not be incurred by current generations to reduce doses that are
 - 7 already low from a holistic risk perspective.
 - 8 • Inventory limits can be used to avoid costs associated with implementing alternatives to
 - 9 reduce large doses that may be incurred from a large radionuclide inventory.

10
11 In addition to the quantitative information discussed above, the licensee may provide regulators
12 with the proportion of resources that they propose to use to achieve the protection of public
13 health and the environment for different timeframes. This information can help identify
14 disproportionate costs and benefits in the proposed approach, and provide transparency to
15 stakeholders. It can also help communicate the proposed approach in terms of the commitment
16 to short- and long-term environmental protection. These resource estimates should only be
17 discounted up to the closure of the facility, as no long-term design changes are expected to be
18 implemented following closure.



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Figure 6-3 Hypothetical Performance Assessment Model Output with the Minimization Parameters

1 The alternatives evaluated under the minimization process should be limited to those that are
2 currently technically feasible. It is not necessary to attempt to project the development of future
3 practices. The cost estimates should reflect the uncertainties associated with the maturity of the
4 technology by considering different ranges of effectiveness for a unit cost or a range of costs for
5 a given effectiveness.

6 **6.2.1.3 Other Decision Analyses**

7
8 Other decision analyses techniques may be applied by licensees and regulators should review
9 each type of analyses on a case-by-case basis. For instance, cost-benefit analyses are used to
10 evaluate alternatives and facilitate decision-making. NRC has developed guidance for cost-
11 benefit analyses applied to environmental reviews (NRC, 2003d, Section 6.7) and waste
12 incidental to reprocessing waste determinations (NRC, 2007a). However, direct application of
13 cost-benefit analyses to the very long timeframes associated with LLW disposal is tenuous
14 because discounting can be difficult, as well as accurately estimating the population surrounding
15 a disposal site thousands of years into the future. In previous staff guidance, NRC has
16 recommended that the monetary value associated with averted future doses should not be
17 discounted in the analyses for application to 10 CFR Part 61 (NRC, 2000c).

18 **6.2.1.4 Other Considerations**

19
20 According to 10 CFR 61.50(a)(1), to the extent practicable, the disposal site shall be capable of
21 being characterized, modeled, analyzed, and monitored. In addition, a licensee must account
22 for uncertainty and variability in the performance assessment analyses. Over the protective
23 assurance period, stability of the disposal site may be difficult to demonstrate if the disposal site
24 is in an unfavorable location. In some circumstances, a licensee may not be able to adequately
25 reflect uncertainties in the long-term technical analyses. In these cases, the licensee or
26 regulator should impose inventory limits as a method to manage the uncertainties that may not
27 be adequately assessed with technical analyses. Example 6.2 provides information on how
28 other considerations can be used to ensure protection of public health and safety during the
29 protective assurance period.

30

Example 6.2

The Radala disposal site is located in a semi-arid environment with a relatively stable present day environment. A license applicant proposes to dispose of a waste stream comprised of large quantities of long-lived waste in the disposal facility. The projected future environment is anticipated to be unstable due to geomorphological processes (e.g., high erosion associated with landform evolution). The performance assessment from the compliance period is used to estimate potential future doses during the protective assurance period. Projected doses to a member of the public are estimated to be approximately 100 mrem/yr. The regulator reviews the analyses and determines that the licensee did not adequately incorporate the uncertainty in erosion rates driven by variability in future climate states. If uncertainty in erosion rates is considered, the projected future doses can be on the order of many thousands of mrem per year. In response to a request from the regulator, the license applicant evaluates different design alternatives and determines that none can be relied upon to significantly reduce the projected future doses or that the alternatives would be prohibitively expensive.

Conclusion: The regulator approves of the application with conditions. The disposal of either limited quantities or concentrations of the waste stream is approved. The regulator agrees with the licensee that no technologically or economically practical alternatives exist to prevent disturbance of the disposal facility by the geomorphological processes. The regulator examined other operating LLW disposal facilities and determined that other facilities have been analyzed for disposal of the waste stream. Other facilities, due to favorable site conditions for long-lived waste disposal, could dispose of the waste stream and are projected to result in a radiation dose to a member of the public of a few mrem per year. Considering the uncertainty and the fact that the license applicant cannot demonstrate long-term stability of the disposal site, the regulator determines that inventory limits should be developed. The regulator provides inventory limits as a license condition that limit the inventory to a fraction of the inventory originally proposed by the licensee. The licensee can determine whether it is economically viable to dispose of the waste stream at the inventory limits.

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7.0 PERFORMANCE PERIOD ANALYSES

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

- (1) Assess how the disposal facility and site characteristics limit the potential long-term radiological impacts, consistent with available data and current scientific understanding.
- (2) Identify and describe the features of the design and site characteristics that will demonstrate that the performance objectives set forth in 10 CFR 61.41(c) and 10 CFR 61.42(c) will be met.

The primary purpose of the performance period analyses is to provide information that demonstrates that releases of long-lived¹ radioactive waste from a disposal facility are minimized to the extent reasonably achievable. The protective assurance period is defined in the regulations as the period from the end of the compliance period through 10,000 years following closure of the site. The performance period is defined in the regulations to be the period of time following the protective assurance period. Performance period analyses are required only if the disposal facility is accepting long-lived waste that has disposal site-averaged concentrations of long-lived radionuclides greater than the values provided in Table A of 10 CFR 61.13(e), or if necessitated by site-specific conditions. Table 7-1 lists long-lived isotopes that may be present in LLW inventories.

The disposal system consists of the disposal units, disposal site, land disposal facility, and surrounding environment. The assessment should evaluate natural and engineered characteristics of the disposal system and describe how those characteristics will reduce long-term impacts. Over the long timeframes of regulatory concern, performance of the disposal system is likely to be driven by the features of the natural system rather than by man-made engineered barriers. The level of detail in the assessment should be risk-informed. The licensee should calculate the expected concentrations of long-lived waste remaining in the disposal site after the protective assurance period to risk-inform the longer-term performance period analyses. In general, the amount of resources and effort devoted to the assessment for the performance period will increase in proportion to the magnitude of the longer-lived radioactive waste inventory, considering both the initial inventory and ingrowth. Table 7-2 provides examples of how performance period analyses may be risk-informed, taking into account the longevity of the inventory and the duration of the hazard it poses.

¹ Long-lived waste means waste containing radionuclides (1) where more than ten percent of the initial activity of a radionuclide remains after 10,000 years (e.g., long-lived parent), (2) where the peak activity from progeny occurs after 10,000 years (e.g., long-lived parent – short-lived progeny), or (3) where more than ten percent of the peak activity of a radionuclide (including progeny) within 10,000 years remains after 10,000 years (e.g., short-lived parent – long-lived progeny). The first part of the definition represents radionuclides with approximately a 3,000 year or longer half-life. Examples of isotopes that are short-lived but produce long-lived progeny are provided in Table 7-1 (e.g., Am-241, Cm-242).

Table 7-1 Long-lived Isotopes Potentially Present in LLW Performance Assessment Inventories

Isotope	Half-life (yr)	Long-lived		LLW PA Inventory ¹	Isotope	Half-life (yr)	Long-lived		LLW PA Inventory ¹
		Parent	Progeny ²				Parent	Progeny ²	
Al-26	7.17 x 10 ⁵	X			U-233	1.59 x 10 ⁵	X	Th-229	Yes
C-14	5,730	X		Yes	U-234	2.45 x 10 ⁵	X	Th-230	Yes
Cl-36	3.01 x 10 ⁵	X		Yes	U-235	7.038 x 10 ⁸	X	Pa-231	Yes
K-40	1.3 x 10 ⁹	X			U-236	2.342 x 10 ⁶	X	Th-232	Yes
Ni-59	7.5 x 10 ⁴	X		Yes	U-238	4.468 x 10 ⁹		U-234	Yes
Se-79	1.1 x 10 ⁶	X			Np-237	2.14 x 10 ⁶	X	U-233	Yes
Zr-93	1.53 x 10 ⁶	X			Pu-238	87.7		U-234	Yes
Nb-94	2.0 x 10 ⁴	X			Pu-239	2.41 x 10 ⁴	X	U-235	Yes
Tc-99	2.14 x 10 ⁵	X		Yes	Pu-240	6.54 x 10 ³	X	U-236	Yes
Pd-107	6.56 x 10 ⁶	X			Pu-241	14.4		Np-237	Yes
Sn-126	1 x 10 ⁵	X			Pu-242	3.76 x 10 ⁵	X	U-238	Yes
I-129	1.6 x 10 ⁷	X		Yes	Pu-244	8.26 x 10 ⁷	X	Pu-240	Yes
Cs-135	3 x 10 ⁶	X			Am-241	432		Np-237	Yes
Sm-146	1 x 10 ⁸	X			Am-242m	16 hr		U-234	Yes
Pm-147	2.62		Sm-147		Am-243	7.38 x 10 ³	X	Pu-239	Yes
Sm-147	1.06 x 10 ¹¹	X			Cm-242	0.446		U-234	Yes
Eu-152	13.3		Gd-152		Cm-243	28.5		Am-243	
Gd-152	1.08 x 10 ¹⁴	X			Cm-244	18.1		Pu-240	
Ra-226	1,600	X		Yes	Cm-245	8.5 x 10 ³	X	Np-237	
Th-229	7.3 x 10 ³	X		Yes	Cm-247	1.56 x 10 ⁷	X	Am-243	
Th-230	7.7 x 10 ⁴	X	Ra-226	Yes	Cm-248	3.39 x 10 ⁵	X	Pu-244	
Th-232	1.41 x 10 ¹⁰	X		Yes	Cf-249	351		Cm-245	
Pa-231	3.28 x 10 ⁴	X			Cf-251	898		Am-243	
U-233	1.59 x 10 ⁵	X	Th-229	Yes	Cf-252	2.64		Cm-248	

¹ Any isotope that is to be disposed of in sufficient quantities should be considered as part of the LLW PA inventory. However, the isotopes with "Yes" are expected to more commonly be a significant isotope in a LLW PA inventory based on past analyses as of the date of this publication. All progeny important for the radiological dose calculations should be considered in the technical analyses. For example, Rn-222 is an important short-lived progeny of Ra-226.

² Only the first long-lived progeny encountered in decay chains are listed in this column.

1 **Table 7-2 Expected Level of Review Effort Associated With Performance Period**
 2 **Analyses**

Radiation Hazard And Duration	Level Of Review Effort	Example
Short-lived, any concentrations	NA	Long-term performance period analyses are not necessary.
Short-lived and low concentrations of long-lived or limited quantities of concentrated long-lived	Low	Using undisturbed concentrations during the performance period, provide analyses showing that the dose to inadvertent intruders meets the compliance period performance objective (e.g., assume no dilution and perform an intruder assessment).
Moderate concentrations of long-lived or moderate quantities of concentrated long-lived	Moderate	Provide analyses showing that the disposal system will limit releases from natural processes and plausible disruptive events ¹ . Estimate the range of doses that may result to intruders and members of the public and demonstrate that they are minimized to the extent reasonably achievable ² . Include uncertainty and variability. Formal peer review of the analyses and results should be considered.
High-concentrations and quantities of long-lived	High	Provide analyses showing that the disposal system will limit releases from natural processes and plausible disruptive events. Estimate the range of doses that may result to members of the public and demonstrate that they are minimized to the extent reasonably achievable. Include uncertainty and variability. Support for the range of impacts should include model support, such as that derived from natural analogs of long-term site evolution. Independent, formal peer review of the analyses, results, and model support should be performed.

3 ¹ Discussed in Section 7.3

4 ² Discussed in Section 7.4.1.1.3

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1 Licensees should provide model support for the performance period analyses; however, that
2 support will likely be less quantitative and involve more expert judgment than model support that
3 would be required for the compliance period and the protective assurance period. Table 7-2
4 shows how the performance period analyses may be risk-informed by licensees. Review
5 methods other than those suggested by the examples in the table may be suitable. The level of
6 review effort should be higher when risks for the performance period are larger. If at all
7 possible, simple, conservative analyses should be used, especially when projected risks are
8 low. For higher hazard and longer-lived wastes, expected scenarios as well as less likely, but
9 plausible, disruptive scenarios (discussed in Section 7.3) should be addressed in the analyses.
10 Licensees should provide model support, as discussed in Section 2.2.3, especially for higher
11 hazard and longer-lived wastes. In order to determine what hazard is posed, it may be useful
12 for licensees to estimate the doses to intruders and public receptors with conservative scenarios
13 and compare those estimates to their expected scenarios. A hazard may or may not translate
14 into risk, but high hazard problems should have more support and independent review relative
15 to low hazard problems.

16
17 The NRC staff developed the concentration values provided in 10 CFR 61.13(e) as a risk-
18 informed screening device to help determine if performance period analyses are necessary for a
19 particular disposal action. The challenge associated with developing criteria for when to
20 perform the performance period analyses, such as these concentration values, is that there are
21 many variables that can influence the magnitude of the impact from the disposal of a particular
22 type of waste. Site-specific design and hydrogeology as well as potential disruptive processes
23 and events will influence which pathways are important and the magnitude of risk associated
24 with the different pathways. In most circumstances, the variability in the analyses results will be
25 larger for calculations supporting demonstration of compliance with 10 CFR 61.41 than those
26 associated with 10 CFR 61.42.

27
28 A key driver of variability in the risk associated with long-lived, mobile isotopes is variability in
29 hydrogeology. The disposal of wastes containing long-lived isotopes near or at the Class A
30 limits can result in drinking water doses that exceed 0.25 mSv/yr (25 mrem/yr) at certain sites.
31 Depending on the site-specific hydrogeology, these water pathway impacts may occur during
32 the compliance period, during the protective assurance period, or during the performance
33 period. For example, it was previously found that the isotopes ^{129}I , ^{99}Tc , ^{36}Cl , and ^{14}C are most
34 problematic because of their relatively high mobility in the environment (NRC, 1982b, p. 5-43).
35 Though the drinking water pathway is discussed in the text above, the concept is not limited to
36 the drinking water pathway. Various site-specific conditions can drive the risk from waste
37 disposal at a site even for waste at the Class A limits (i.e., waste that is generally perceived by
38 most licensees and stakeholders to be fairly benign). The assumption that disposal of Class A
39 waste is inherently compliant with the performance objectives may not always be correct,
40 particularly for waste classified using 10 CFR 61.55(a)(6).

41
42 Some sites, designs, and waste streams may require performance period analyses even though
43 the average concentrations of long-lived radionuclides are below those provided in
44 10 CFR 61.13(e). The types of site-specific conditions that could trigger the need to conduct
45 performance period analyses include, but are not limited to:

- 46
47 • Limited dilution or dispersion (e.g., sites with high infiltration and low groundwater
48 velocities) at a site with a potable groundwater pathway and long travel times.

- 1 • Highly-soluble wasteforms combined with resistive engineered barriers that fail
2 discretely.
- 3 • Ingrowth of progeny that increases the radiotoxicity of the waste significantly during the
4 performance period compared to the radiotoxicity at the end of the compliance period.
- 5 • Erosion rates and engineered barrier performance that result in limited protective cover
6 remaining over the waste during the performance period.
- 7 • Gaseous releases from the ingrowth of radon being a significant exposure pathway
8 during the performance period.

9 The importance of the conditions described above is conditional on the timing (i.e., delay) of a
10 potential radioactive release. However, delay by itself is generally not enough to result in a
11 significant impact during the performance period from waste disposal at the Class A limits. One
12 or more of the conditions listed above must also be present. Although the travel time concept
13 presented here is focused on the time from release to exposure of the public, it is not limited to
14 hydrologic transport through groundwater. Transport through surface water or the atmosphere
15 could also be considered though the travel times through those pathways are generally much
16 shorter. Performance period analyses are required when the isotopic concentrations exceed
17 the values specified in 10 CFR 61.13(e), or if site-specific conditions warrant confirmation that
18 the performance objectives will be met (see Example 7.1).

19 **7.1 Estimation of Disposal Site-Averaged Isotopic Concentrations**

20
21 Table 7-3 in this document is the same as Table A in 10 CFR 61.13(e). It provides the
22 concentrations values that a licensee must use to determine if performance period analyses are
23 necessary for their proposed disposal action. These concentration values, for radionuclides
24 other than the long-lived alpha-emitting non-transuranic isotopes, are the Class A waste
25 concentrations provided in Table 1 of 10 CFR 61.55. Long-lived alpha-emitting non-transuranic
26 isotopes are included at the same concentrations as the long-lived transuranic isotopes. During
27 the original development of the 10 CFR 61.55 waste classification tables, long-lived alpha-
28 emitting non-transuranic isotopes were not included because it was expected that LLW would
29 not contain those isotopes in sufficient quantities and concentrations to impact public health and
30 safety from their disposal (NRC, 1982b). However, there is no compelling reason for the long-
31 lived non-transuranic isotopes to be treated differently in the technical analyses if both
32 transuranic and non-transuranic isotopes are included in the wastes proposed for disposal. The
33 radiological risk will be determined in part by the dose conversion factors of individual isotopes
34 and the concentration of those isotopes. There is variability in dose conversion factors from
35 isotope to isotope (EPA, 1988). NRC decided to reduce this variability when deriving the
36 10 nanocuries per gram (nCi/g) concentration value for all transuranic isotopes in Class A waste
37 (NRC, 1982b). The dose conversion factors for non-transuranic isotopes are generally
38 comparable to the transuranic isotopes, and NRC believes it is appropriate to simplify the
39 consideration of variability. The concentrations provided in Table A of 10 CFR 61.13(e) are only
40 to determine if performance period analyses are necessary.

Example 7.1

A disposal site is located in a humid, oxidizing environment with a shallow water table and potable groundwater. Infiltration that will flow through the waste to the saturated zone is not expected to experience significant dilution. The groundwater flow velocity is relatively slow, such that most of the discharge from the aquifer is balanced by recharge from infiltration. In order to control infiltration, the licensee intends to use geomembranes with a design-life of approximately 1,500 years. The water table is located within a geologic unit that is mostly clay with good properties with respect to slowing radionuclide transport. The waste streams being disposed of are dominated by Tc-99 and material contaminated with soluble forms of DU.

Conclusion: The licensee develops waste acceptance criteria that specify isotopic concentrations for anticipated waste streams such that the sum of fractions on a disposal site-averaged basis is ≤ 0.5 of the Table A values in 10 CFR 61.13(e), thereby limiting the types of waste that can be received to concentrations less than the Table A values in 10 CFR 61.13(e). The licensee develops compliance period calculations that show the performance objectives are likely to be met for the next 10,000 years, primarily as a result of the long travel times from the waste to a potential receptor location. Their intruder assessment shows that potential impacts to intruders are well within the established limits. Because the site has a number of characteristics that could result in significant performance period impacts (e.g., resistive engineered barriers, soluble waste streams, limited dilution, waste with ingrowth of progeny, and long travel times), the licensee develops performance period analyses to demonstrate that 10 CFR 61.41(c) is met. The licensee chooses to extend the compliance period analyses with conservative parameters to provide a comparison of the estimated impacts during the performance period with those for the compliance period.

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A licensee should estimate the disposal site-averaged isotopic concentrations of radionuclides to determine if performance period analyses are necessary. Disposal site-averaged concentrations can include the volume of the waste, uncontaminated materials used to stabilize waste or reduce void space within waste packages, the volume of uncontaminated materials placed within the disposal cells, and the volume of engineered or natural materials used to construct the disposal cells. For the purpose of determining if performance period analyses are necessary, the licensee should base the disposal site-averaged concentrations on the total amount of waste averaged over the total volume of all disposal cells. Though the disposal site definition includes a buffer zone, the buffer zone should not be included in the calculations. For radionuclides where the concentration shown in Table 7-3 is based on mass and not volume, the licensee can use the total mass of the different materials within the disposal cells.

A reviewer should consider the variability in radionuclide concentrations over the disposal site. The significance of variability will need to be interpreted in the context of the particular technical analysis. For the purposes of determining if performance period analyses should be performed by a licensee, the variability in concentrations of radionuclides over the disposal site should translate into a significant change in a performance metric (e.g., dose, environmental concentration, flux rate to the environment). Some metrics will be more sensitive to inter-site

1 variability in radionuclide concentrations than others, as a result of different averaging volumes
 2 when calculating the metric. For instance, the concentrations in an aquifer may have more
 3 variability compared to a drinking water dose metric because the aquifer concentrations are
 4 averaged over some volume, due to extraction of the aquifer water in a well, in order to
 5 calculate the drinking water dose (i.e., wellbore dilution).

6
 7 Most disposal facilities are expected to dispose of waste containing a mixture of different
 8 isotopes. In order to determine if performance period analyses are necessary, a sum of
 9 fractions approach must be used, as required by 10 CFR 61.13(e). Licensees should estimate
 10 the disposal site-averaged concentrations of each isotope. They should divide the resultant
 11 values by the concentrations found in Table 7-3 to estimate a fraction for each isotope, and then
 12 sum the fractions over all isotopes. If the total is greater than 1.0, then licensees are required to
 13 develop performance period analyses (10 CFR 61.13(e)). Examples 7.2 and 7.3 provide sum of
 14 fractions (SOF) calculations.

15
 16 **Table 7-3 Disposal Site-Averaged Isotopic Concentrations that Require**
 17 **Performance Period Analyses**

Radionuclide	Concentration (Ci/m ³)
C-14	0.8
C-14 in activated metal	8
Ni-59 in activated metal	22
Nb-94 in activated metal	0.02
Tc-99	0.3
I-129	0.008
Long-lived alpha-emitting nuclides	¹ 10
Pu-241	¹ 350
Cm-242	¹ 2,000

18 ¹ Units are nCi/g
 19

20 **7.2 Disposal Site Characteristics that Enhance Long-Term Isolation**
 21

22 The remainder of this section focuses on the long-term analyses that licensees should
 23 complete. The regulatory requirements are not prescriptive with respect to the type of analyses
 24 that must be performed. Licensees may use any analyses (e.g., screening, quantitative
 25 probabilistic) considered sufficient to demonstrate that the regulatory requirements will be met.
 26 However, there are limits to the analyses of projected performance over very long timeframes
 27 (e.g., tens of thousands of years) and how much confidence a licensee should place in the
 28 results of the analyses. Disposal sites and near-surface disposal facility designs that have more
 29 disposal site characteristics that enhance long-term isolation may be more likely to achieve
 30 long-term isolation of waste from the accessible environment if they demonstrate one or more of
 31 the characteristics cited in Table 7-4.
 32
 33

Example 7.2

The total volume of disposal cells for existing waste is 400,000 m³. The inventory of waste located in the facility is comprised of: 50,000 m³ of C-14 containing waste at 0.2 Ci/m³, 200,000 m³ of waste containing C-14 at 0.1 Ci/m³ and I-129 at 0.002 Ci/m³, and 50,000 m³ of Tc-99 containing waste at 0.01 Ci/m³. The uncontaminated fill and material used to construct the cells represents 100,000 m³.

Conclusion: The licensee uses the values in Table A to calculate the volume-averaged SOF per the following equation. This equation is used to calculate the SOF for n waste streams containing m isotopes. V is the volume, C is the concentration on a volumetric basis, and CA is the value from Table A for the particular isotope.

$$SOF = \frac{1}{V_T} \sum_{i=1}^n \left(V_i \sum_{j=1}^m \frac{C_{i,j}}{CA_{i,j}} \right)$$
$$SOF = \frac{1}{400,000 \text{ m}^3} * \left(50,000 \text{ m}^3 \left(\frac{0.2}{0.8} \right) + 200,000 \text{ m}^3 \left(\frac{0.1}{0.8} + \frac{0.002}{0.008} \right) + 50,000 \text{ m}^3 \left(\frac{0.01}{0.3} \right) \right) = 0.223$$

Because the SOF is less than 1, performance period analyses are not required.

Table 7-4 describes the characteristics that will enhance isolation at most, but not all, disposal sites. Individual characteristics may not apply at a specific site. For example, low porosity in a cementitious wastefrom generally reduces the potential for subsidence and reduces leaching. However, use of a low porosity cementitious wastefrom 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 wastefroms is generally favorable, in this specific example it may not be. Some of the characteristics listed in Table 7-4 apply to the design of disposal facilities while others apply to the site characteristics.

7.3 Scope of the Performance Period Analyses

The performance period analyses should provide information about the performance of the disposal system under a range of conditions that represent expected scenarios, as well as less likely, but plausible, scenarios that may have significant consequences. Licensees should consider the range of conditions consistent with the site suitability analysis (described in Section 5.0), including the FEPs analysis (Section 2.0). Less likely but plausible scenarios include those that are unlikely to be observed (e.g., as low as a 10 percent chance of occurrence over the analyses timeframe), as well as those that are expected to be observed over the analysis timeframe. Performance period analyses for various sites may have different timeframes associated with them owing to differences in radionuclide inventories as well as differences in geologic settings. Therefore, a single event frequency (i.e., 10⁻⁵/yr) cannot be defined for the purposes of this particular regulatory requirement.

Example 7.3

The licensee in Example 7.2 would like to dispose of a new waste stream but they are unsure if they would need to develop performance period analyses.

The new waste stream is a particulate waste. The raw particulate waste contains average concentrations of 0.7 Ci/m³ Tc-99, 1.2 Ci/m³ C-14, and 90 nCi/g of long-lived, alpha-emitting radionuclides. The total volume of raw waste is 100,000 m³. In order to reduce the potential for dispersion, the particulate waste is solidified in grout prior to disposal. The ratio of grout to waste inside the disposal package is 3 to 1 (stabilizer ratio). Because the density of the grout and this particular waste stream are similar, the 3 to 1 ratio holds for both a mass and volume basis.

The drums of waste will be stacked within the disposal cells achieving a disposal cell packing efficiency of 67% (i.e., the ratio of cell volume occupied by waste packages to the total internal volume of the cell – *Cell Eff.*). In addition, the disposal cells are constructed of a variety of natural materials to provide structural stability, to reduce water inflow to the waste, and to provide chemical retention of the waste. The volume of material comprising the disposal cells is 30% of the total internal cell volume available for disposal (i.e., *Inert frac.*).

Conclusion: First the licensee calculates the cell volume required for the new waste, V_{Tn} :

$$V_{Tn} = \text{Waste Volume} * (1 + \text{Stabilizer Ratio}) * \frac{1}{\text{Cell Eff.}} * (1 + \text{Inert frac.})$$

$$V_{Tn} = 100,000 \text{ m}^3 * (1 + 3) * \frac{1}{0.67} * (1 + 0.3) = 776,000 \text{ m}^3$$

Next the licensee calculates the SOF for the new waste stream (SOF_n) containing m isotopes, where C_m , V , and CA_m are the concentration, volume, and long-lived waste concentration (for isotope m from Table A of 10 CFR 61.13(e)). Only one new waste stream is considered, so the equation from Example 6.2 is simplified:

$$SOF_n = \frac{V}{V_{Tn}} \sum_{i=1}^m \frac{C_i}{CA_i}$$

$$SOF_n = \frac{100,000}{776,000} \left(\frac{0.7}{0.3} + \frac{1.2}{0.8} + \frac{90}{10} \right) = 1.65$$

Then the licensee calculates the average sum of fractions for both old and new waste where V_T is the combined volume of old and new waste (total disposal cell volumes) and SOF_o is the sum of fractions for the old waste:

$$SOF = \frac{1}{V_T} * (SOF_n * V_{Tn} + SOF_o * V_{To})$$

$$SOF = \frac{1}{(776,000 + 400,000)} * (1.65 * 776,000 + 0.223 * 400,000) = 1.16$$

In this case the SOF is greater than 1 on a disposal site-averaged basis when the new waste stream is combined with the existing waste stream. Therefore, performance period analyses are required to determine if the new waste stream can be safely disposed of in the facility.

1 **Table 7-4 Disposal Site Characteristics that Could Enhance Long-Term Isolation**

Characteristic¹	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

2 ¹ Highlighted characteristics are associated with 10 CFR 61.50 site suitability characteristics

3

1 FEPs defining the natural and engineered systems as well as assumptions about future human
2 behavior will be needed for the performance period analyses. The challenge for performance
3 period analyses is to provide credible assessments of the future evolution of the disposal
4 system while avoiding open-ended speculation. Near-surface disposal introduces specific
5 challenges over the long-term because environmental processes can have complex, dynamic,
6 and nonlinear responses. The NRC staff believes that the approach recommended in the
7 following sections is suitable for defining the scope of the performance period analyses for near-
8 surface disposal. The goal of the long-term analyses is to understand the safety implications of
9 the type of waste being disposed in the near surface and not to precisely estimate the future
10 evolution of the surface of the earth. The goal is to provide a perspective on how the hazard
11 may evolve over time (e.g., persistence of long-lived radionuclides and potential for ingrowth of
12 risk significant daughters) and implications for near surface disposal.

13
14 Disposal of high-specific activity waste, if improperly managed by a licensee, poses the greatest
15 radiological risk to public health and safety. It would be very difficult for a licensee to
16 demonstrate with reasonable assurance that public health and safety is protected from the
17 disposal of the high-specific activity waste at a site with unfavorable site characteristics because
18 the margin for error is small. For example, accidental release of a relatively small quantity of Sr-
19 90 into an aquifer at the West Valley Demonstration Project resulted in a significant ground
20 water plume requiring remediation (NYSDEC, 2008). Only a small amount of high-specific
21 activity waste released into the environment can cause significant problems. For the
22 performance period, the margin for error is not as small because the high-specific activity
23 fraction of the waste has decayed. The specific activity of the material remaining in the disposal
24 site is much lower compared to the waste when first disposed. Furthermore, because of the
25 long timeframes involved, a licensee may consider the performance objectives in Subpart C
26 when evaluating whether their site meets the site suitability requirements in 10 CFR 61.50 for
27 the performance period. For example, a disposal site might have some projected seismic
28 activity (10 CFR 61.50(a)(4)(iii)) sometime after the 10,000-year protective assurance period.
29 However, because of the uncertainty with events at long timeframes, future seismic activity
30 would only disqualify the site if the licensee was unable to demonstrate that the performance
31 objectives would be met assuming this seismic activity. Therefore, it is acceptable for the
32 performance period for a licensee to evaluate the significance of the site characteristics using
33 technical analyses.

34 **7.3.1 Features, Events, and Processes**

35
36 The objective of the performance period analyses is to provide information to decision-makers
37 about disposal system performance under various scenarios. Licensees should assess the
38 uncertainties, because they are likely to be large, and present the results of the assessment
39 using a balanced approach. Reviewers should not hold the performance period analyses to a
40 level of proof that is not attainable. In comparison with the compliance period, the performance
41 period analyses will be more susceptible to bias because objective supporting information will
42 be more limited.

43
44 Different near-surface LLW disposal facilities may have significantly different characteristics and
45 may contain different wastes. The FEPs for one disposal site may be substantially different
46 from those at a different site. Identification of the FEPs relevant to the performance period will
47 be site-specific. Section 2.5 describes the FEP process that may be used by a licensee to
48 develop the scope of the technical analyses (e.g., performance assessment). This section of

1 the guidance document does not reiterate the general information relevant to FEPs analysis
2 found in Section 2.5.

3
4 A licensee may extend compliance period or protective assurance calculations without
5 modification provided that the calculations are complete with respect to including key FEPs
6 relevant to the performance period. The compliance or protective assurance period calculations
7 may not be complete with respect to the scope of the performance period analyses. It will be
8 necessary for the licensee to communicate the additional uncertainties associated with events
9 and processes that may occur in the long-term performance period if they are not represented in
10 the compliance or protective assurance period analyses. The analyses that are developed for
11 the compliance period or protective assurance period may not be sufficient for the performance
12 period analyses if (1) disruptive processes are expected to occur during the performance period
13 that have not been included in the compliance period or protective assurance period analyses,
14 or (2) if the cumulative impact from repetitive events over the longer timeframes is not included
15 and the repetition of those processes and events could lead to significant impacts. It is
16 appropriate for a licensee to consider potentially beneficial natural processes (from a risk
17 reduction perspective) such as dispersion and dilution in addition to detrimental processes. In
18 general, the greater the geological and geomorphological stability a potential disposal site
19 possesses, the greater the likelihood that FEPs that may occur in the performance period will
20 have already been represented in the licensee's compliance period or protective assurance
21 period analyses. However, the representation of a particular FEP in the compliance period or
22 protective assurance period analyses may be different in the performance period analyses.
23 Even if the same set of FEPs may be appropriate for all analyses, they may be represented
24 differently in each analysis.

25
26 As discussed in Section 2.5.3.1, 10 CFR Part 61.50 provides the disposal site suitability
27 requirements for the land disposal of LLW. The process to determine if some of these criteria
28 will be met is complementary to the FEPs process (discussed in Section 7.3.2). The criteria
29 from 10 CFR Part 61.50 that best lend themselves to FEPs analysis are
30 10 CFR 61.50(a)(2)(i-iv) and 10 CFR 61.50(a)(4)(ii-iv). Some of the 10 CFR 61.50 regulatory
31 requirements list FEPs that a disposal facility must have (e.g., sufficient depth to water table),
32 whereas other requirements list FEPs or conditions that a disposal facility must not have (e.g.,
33 exploitable natural resources). Since these are regulatory requirements, the FEPs process for
34 the performance period should analyze the FEPs related to 10 CFR 61.50(a)(2)(i-iv) and
35 10 CFR 61.50(a)(4)(ii-iv).

36
37 Many potential scenarios involving certain forms of flooding, landslides, earthquakes, and
38 volcanoes will not be evaluated in the performance period. Potential sites containing FEPs that
39 occur with such frequency and extent to significantly affect the ability of the disposal site to meet
40 the performance objectives of 10 CFR Part 61 Subpart C for the compliance period would not
41 be considered for LLW disposal. These scenarios may also preclude defensible modeling and
42 prediction of long-term impacts.

43
44 The number of possible scenarios that can be developed will be reduced after screening
45 potential disposal systems based on the site suitability FEPs. However, FEPs that have been
46 screened from further consideration in the compliance period or protective assurance period
47 may not be able to be screened from further consideration for the performance period analyses.
48 For example, the rate of erosion may be estimated to be sufficiently low over the compliance
49 period, and as a result, the FEP of erosion is not within the scope of the compliance period

1 analyses. However, over the analyses timeframe for the performance period the rate of erosion
2 may be significant such that the FEP should be included within the scope of the performance
3 period analyses. Therefore, the compliance period and protective assurance period FEP
4 processes will reduce the FEPs applicable to the performance period but some of the FEPs
5 eliminated in the compliance period or protective assurance period may apply for the
6 performance period.

7 **7.3.2 Screening of Features, Events, and Processes Based on the Requirements** 8 **in 10 CFR 61.50**

9
10 A licensee should complete the FEP screening and scenario development process for the
11 performance period in a risk-informed manner. Whereas some of the site characteristics for the
12 compliance period are either required to be present or to be absent (i.e., hydrological site
13 characteristics for 500 years) because they are precursors of poor long-term performance, all of
14 the site suitability characteristics for the performance period may be evaluated considering
15 radiological risk.

16
17 Appendix B presents hazard maps that the NRC staff created related to the features and
18 phenomena of the 10 CFR 61.50 criteria. The hazard maps provide an illustration of the FEPs
19 associated with the site suitability requirements. The maps cannot be displayed in this
20 document at sufficient size to be used to determine if any specific location would be impacted by
21 one of these phenomena. The figures only provide an illustration of potentially impacted areas.

22
23 Regulators should not use the hazard maps in Appendix B to prohibit disposal because the
24 resolution of the maps and the precision and accuracy of the techniques used to generate them
25 may not be sufficient for site-specific evaluations. However, regulators should use the maps to
26 determine when greater review effort and more technical basis should be expected for a
27 licensee's site-specific evaluation. In addition, the data used to produce these maps could be
28 used, via Geographic Information System (GIS) software, to perform screening-level FEPs
29 analyses. However, the data used to produce these figures in Appendix A were not collected at
30 a scale of resolution sufficient to perform detailed site-specific evaluations by either regulators
31 or applicants.

32
33 For the performance period analyses, FEPs screening based on the requirements in
34 10 CFR 61.50 does not need to be resource intensive relative to the other steps in completing
35 the technical analyses. Background information and knowledge of the geologic history of the
36 site can be used by qualified specialist(s) to evaluate the likelihood of a FEP being present at a
37 potential disposal site during the performance period. This evaluation is a qualitative exercise
38 using information on the past history of a disposal system. The phenomena and features that
39 have occurred there in the past can be used to make judgments about the future and to help
40 make screening determinations. For example, a disposal system may be near a current
41 floodplain but outside of the influence of its associated processes. A qualified specialist may
42 examine the location, nearby topography, and the past history and events, and be able to
43 provide information on the potential for future floodplain formation at the disposal site. With
44 diverse information drawn together from various sources, a licensee may be able to create a
45 sufficient technical basis that supports the exclusion of a floodplain or a near-surface water table
46 forming at or near the proposed disposal site for at least 10,000 years. However, for the
47 performance period, information from the disposal system may point to renewed flooding of the

1 area or it may simply be insufficient to form a basis to screen the process out. In such a case,
2 the licensee would include floodplain formation in the assessment for the performance period.

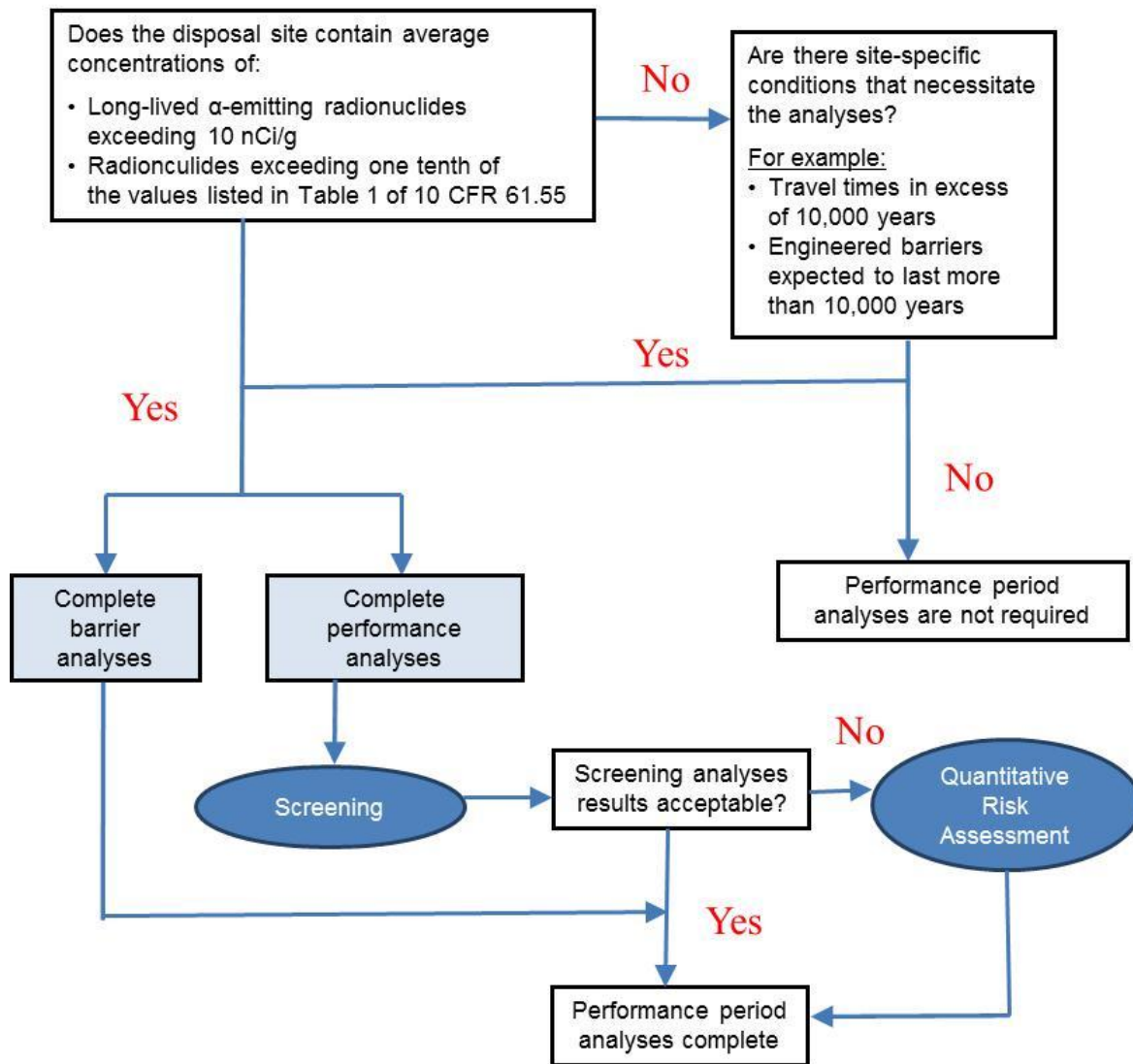
3 **7.3.3 Future Human Behavior**

4
5 FEPs that describe future human behavior in the performance period should be consistent with
6 present knowledge of the conditions in the region surrounding the disposal system. It is not
7 necessary for a licensee to project changes in society, changes in human biology, or increases
8 or decreases in human knowledge or technology. The selection of receptor scenarios and
9 exposure pathways in the performance period analyses should be limited to the consideration of
10 the natural variability in conditions, processes, and events.

11
12 Over long timeframes, the future environmental conditions may be significantly different from the
13 present day. If shorter term analyses limited the behavior, characteristics, and pathways of
14 receptors based on present-day conditions, the licensee should assess the impact from
15 *significant* changes in climatic or environmental conditions using stylized receptor scenarios
16 (see Sections 2.2.4.1 and 2.2.4.2). As necessary, the behavior of potential receptors over the
17 performance period should be modified using present-day climatic analog locations. For
18 example, ground water may not be potable in the present day, but the long-term analyses could
19 examine whether that site characteristic is robust under future climate states. If licensees were
20 to provide a side-by-side comparison of the assumed characteristics of receptors (e.g.,
21 pathways, consumption rates, and exposure times) with those of generic “screening” receptors
22 used in the dose analyses, the reviewer could determine the importance of the assumed
23 receptor characteristics. This sort of comparison is strongly recommended. Generic receptor
24 characteristics are found in a variety of documents (NRC, 1992; NRC, 1981a; NRC, 1982b).
25 This type of comparison is also good practice for compliance period and protective assurance
26 period assessments. Estimates of future disposal site performance that are primarily based on
27 the engineered design, waste characteristics, and site characteristics are likely to be less
28 speculative than estimates that rely on assumptions about future human behavior.

29 **7.4 Analyses for Long-Lived Waste**

30
31 The goal of the performance period analyses is to demonstrate how the disposal facility has
32 been sited and designed to minimize long-term impacts and to provide an indication of the
33 potential long-term performance. The term “analyses” is used here to describe different types of
34 evaluations that may be performed, some of which may be quantitative and others that may be
35 more qualitative. A description of barrier capabilities and design considerations, in addition to a
36 conservative screening evaluation, may be sufficient for lower-risk systems (e.g., limited
37 quantities and low concentrations of long-lived waste). Quantitative risk assessment of long-
38 term performance may be necessary for higher-risk systems (e.g., large quantities of
39 concentrated, long-lived waste). Figure 7-1 is a diagram of the recommended analyses
40 approach for the performance period.



1
2
3
4
5

Figure 7-1 Recommended Approach to Conducting Performance Period Analysis

1 The analyses for the performance period are not intended to be a prediction concerning future
2 system states of the LLW disposal system. The analyses associated with the performance
3 period should represent a credible technical effort using available data and current scientific
4 understanding to assess the long-term performance of the waste disposal facility, including
5 consideration of uncertainties.
6

7 Long-term analyses may have limited data available or data that is highly variable spatially and
8 temporally. Licensees should consider two types of data representation in their assessment of
9 long-term impacts: expected values (e.g., central tendency) and bounding values. Use of
10 expected values, such as the median, can convey the most likely outcome. When expected
11 value calculations are complemented with bounding value calculations, the potential impact of
12 uncertainty on the expected outcome can be conveyed. For the expected value calculations to
13 be useful, the expected values must be representative of the site-specific conditions and
14 features. Expected value calculations must have adequate supporting information to be of utility
15 to regulators and other stakeholders. Bounding values may be necessary when data are not
16 available or are very sparse, or formal expert judgment may be necessary.
17

18 Although the use of bounding values may be necessary, the NRC staff recommends that a
19 licensee use caution in the use of bounding values for performance assessment or other
20 analyses used to assess long-term performance. Many environmental systems can have
21 complex and nonlinear responses, making selection of a bounding value for a specific
22 parameter challenging, if not intractable. An appropriate bounding value may not be intuitive
23 and it may only be bounding locally and not globally. In addition, the compound effect of
24 selecting numerous bounding values in the analyses can result in non-physical results. For
25 example, it would be unreasonable for a licensee to evaluate a high-energy disruptive process
26 that destroys the engineered barriers of the waste disposal facility without resultant dispersion
27 and dilution of the waste. Even in hypothetical bounding calculations, it is useful to provide
28 some context for the reasonableness of the calculations.

29 **7.4.1 Types of Analyses**

30
31 The analyses for the performance period may be quantitative, semiquantitative or qualitative in
32 nature, depending on the waste characteristics or other factors. As discussed previously, the
33 performance period analyses should be risk-informed. A number of approaches are acceptable
34 for providing information on long-term performance. The NRC staff recommends that licensees
35 perform two sets of analyses for the performance period:
36

- 37 • Performance analyses to demonstrate that releases from disposal of long-lived waste
38 will be minimized to the extent reasonably achievable for the performance period
- 39 • Barrier analyses to understand the performance of engineered and natural barriers

40 **7.4.1.1 Performance Analyses**

41
42 The NRC staff recommendation for conducting performance period analyses is to first employ
43 simple, conservative screening analyses. The screening analyses may identify that the
44 radiological risks are acceptable or that allowable limits (see Section 9.0) or other controls may
45 be necessary. If the results of the screening analyses are not acceptable, a licensee may limit
46 disposal of certain types of waste. In addition, quantitative performance period analyses may

1 be performed to determine if the expected radiological risks² to the public from the disposal
2 action are acceptable. The results of refined performance period analyses may demonstrate
3 that the radiological risks are acceptable whereas the results of the conservative, screening
4 analyses may not.

5 7.4.1.1.1 Screening Analyses

6
7 The recommended first step for performance period analyses is to perform simple, conservative
8 screening analyses. The benefit of screening analyses is that they are relatively easy to
9 perform and document, therefore, they are easier for stakeholders to review and understand,
10 often facilitating decision-making. Screening analyses will be significantly less resource
11 intensive for a licensee compared to full probabilistic multi-physics simulations. Screening
12 performed with conservative parameters and calculations are not radiological risk calculations
13 and should not be interpreted as such. They should be clearly described as hypothetical and
14 pessimistic with the objective of identifying whether the potential for unacceptable radiological
15 risk to a member of the public and inadvertent intruder in the performance period exists. Many
16 beneficial features, processes, and characteristics may be purposely ignored in the calculations.
17 If the estimated doses to the public and intruder from the screening analyses are below the
18 limits provided in the 10 CFR 61.41(a) and 10 CFR 61.42(a) performance objectives, additional
19 performance period analyses are not necessary.

20
21 The NRC staff cannot determine a priori the appropriate conservative screening analyses for all
22 potential designs, waste streams, and disposal sites. Conservatism may be defined differently
23 for different decisions. However, for all sites, licensees should provide and reviewers should
24 evaluate:

- 25
- 26 • a list of the potential radiation exposure pathways to the public and intruder from
27 disposed waste
- 28 • a description of the pathways expected to be most significant for releases
- 29 • the technical basis for the conservatism of the screening analyses
- 30 • a discussion of how the parameterization and representation of the screening analyses
31 has accounted for uncertainty and variability
- 32 • a description of the barriers and processes that reduce or mitigate releases

33 For many disposal sites, a potable groundwater pathway will be a primary pathway for releases
34 to the environment. A conservative screening analysis for the groundwater pathway would be
35 one for which all waste inventory is available for release, solubility limits are not applied or are
36 set at conservative values, and delays due to sorption during transport are eliminated by setting
37 distribution coefficients to zero or very small values. However, the physical limitations on mass
38 transport processes would still be included in waste release modeling. For example, if a waste
39 container had a pore volume of X and the volumetric flow rate into the container was a small
40 fraction of X per unit time, the exchange process should still be included in the simulation. In

² Other metrics such as fluxes of radionuclides in the environment or concentrations of radionuclides in the environment may also be used. However, radiological doses are used in the compliance period and provide an apples-to-apples comparison for regulatory analysis.

1 addition, the dilution during transport arising from the geometry of the waste, hydrogeological
2 system, and infiltration processes should be included in the screening assessment.

3 7.4.1.1.2 Quantitative Analyses 4

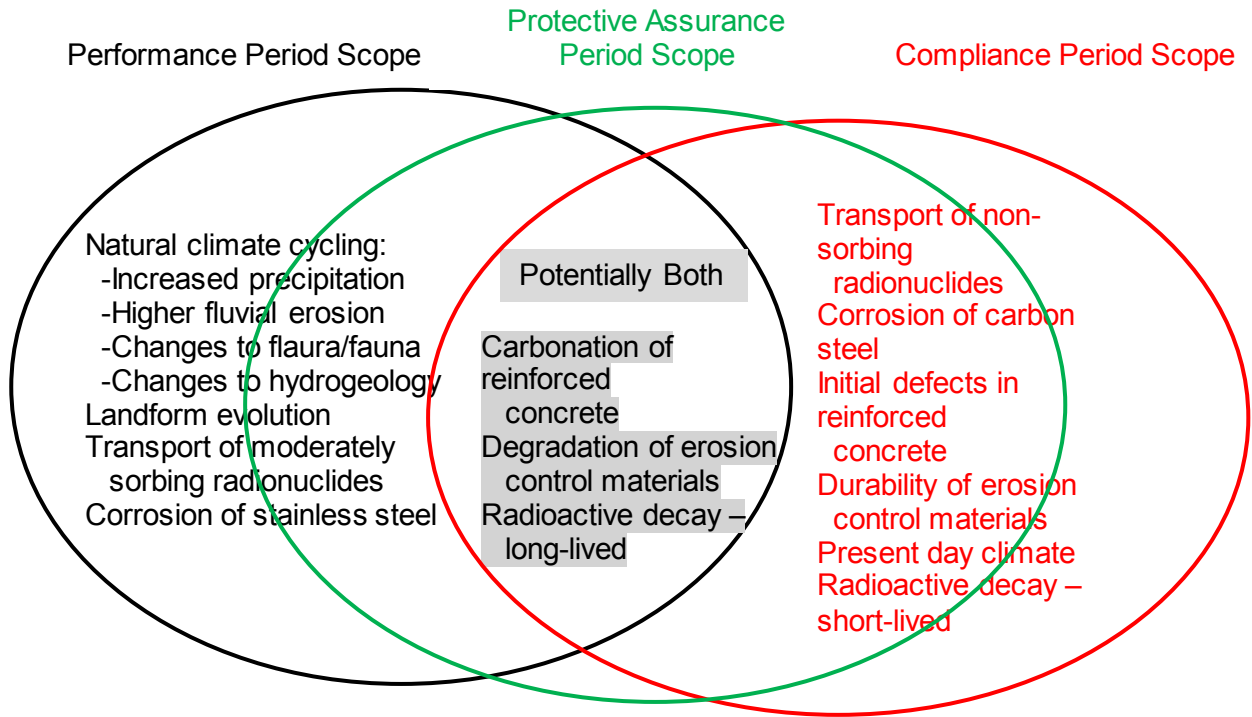
5 If screening analyses have been performed and the projected results are not acceptable (see
6 Section 7.4.1.1.3), then a licensee may modify their facility design, develop limitations on the
7 types of waste that are acceptable for disposal, or perform additional analyses. A licensee may
8 develop performance period analyses to demonstrate that the 10 CFR 61.41(c) and
9 10 CFR 61.42(c) requirements will be met.

10
11 In many respects, the analyses that a licensee may perform for the performance period will be
12 similar to the performance assessment and intruder assessment completed for the compliance
13 period and protective assurance period. The guidance provided in Sections 2.0, 3.0, and 4.0 for
14 the compliance period and in Section 6.0 for the protective assurance period is applicable to the
15 performance period analyses. One primary difference is that licensees will need to consider the
16 additional uncertainties that the long timeframes associated with the performance period
17 introduce. In addition, the metric licensees must use to determine if the 10 CFR 61.41(c) and
18 10 CFR 61.42(c) requirements will be met is to minimize releases to the extent reasonably
19 achievable. Unlike the requirements presented in 10 CFR 61.41(b) and 10 CFR 61.42(b) for the
20 protective assurance period, there is no dose goal associated with the performance period
21 analyses.

22
23 Uncertainties associated with the performance period may be larger than those associated with
24 the compliance or protective assurance periods. As the timeframe for the analyses is extended,
25 temporal processes that have a rate that is insufficient to result in a significant change to
26 performance prior to 10,000 years may be significant when evaluated for the longer
27 performance period. For example, carbonation of a cementitious barrier may be sufficiently
28 slow such that the passivation of rebar is not affected over the 1,000 year compliance period,
29 and even the 10,000 year protective assurance period. However, the rate of carbonation could
30 be sufficient enough to reduce the protective passivation of the rebar after the protective
31 assurance period, leading to deterioration or failure of the cementitious barrier during the
32 performance period.

33
34 Figure 7-2 is an example of the scope of the technical analyses for the compliance period,
35 protective assurance period, and performance period for a hypothetical site. Figure 7-2 has
36 shaded areas to show: that some processes and events will only be applicable to the
37 compliance period or protective assurance period, that some will be only applicable to the
38 performance period, and that others will need additional analyses to determine their
39 applicability. The scope of the analyses for the protective assurance period may include both
40 short- and long-term processes and events depending on the type of waste that is disposed. A
41 licensee will assess some processes in the performance assessment for the compliance period
42 and/or the protective assurance period, whereas others may clearly be applicable only to the
43 performance period. In the quantitative analyses for the performance period, a licensee should
44 assess those FEPs that were determined to be insignificant for the compliance period and/or the

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Figure 7-2 Scope of the Technical Analyses for the Compliance Period, Protective Assurance Period, and Performance Period for a Hypothetical Site

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protective assurance period based on rates that were too slow or likelihoods that were too low. The licensee should determine if those FEPs are relevant to the performance period. It may be useful for a licensee to perform an iterative assessment to determine the appropriate scope of the performance period analyses.

9

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7.4.1.1.3 Minimize Radioactive Releases to the Extent Reasonably Achievable

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The performance metrics a licensee must apply to the assessment of long-term releases during the performance period is to minimize releases to the extent reasonably achievable (10 CFR 61.41(c)) and to minimize exposures to any inadvertent intruder to the extent reasonably achievable (10 CFR 61.42(c)). The metrics afford flexibility to a licensee to consider socioeconomic factors when assessing long-term protection of public health and safety. The requirements to minimize releases and exposures to the extent reasonably achievable are intended to be conceptually similar to different aspects of the ALARA requirement found in 10 CFR Part 20, optimization, and traditional cost-benefit analyses (see Section 6.0).

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Dose limits are not established for the performance period in 10 CFR 61.41(c) and 10 CFR 61.42(c). A quantitative ALARA analysis cannot be completed in the traditional sense (i.e., estimate the cost for further reducing doses below a dose limit). Instead, the requirement of the performance period quantitative analyses is for a licensee to demonstrate that releases will be minimized to the extent reasonably achievable.

The NRC has developed a policy to inform regulatory decision-making (see Section 6.2.1.2).

1 Because of the problems associated with discounting over long timeframes, the NRC staff
2 recommends that licensees should provide the proportion of resources that are proposed to be
3 used to achieve protection of public health and the environment for different timeframes. These
4 resource estimates should be provided in present day values. Timeframes to consider may
5 include:

- 6
- 7 • the institutional control period (100 years)
- 8 • the Class C waste intruder barrier period (500 years)
- 9 • the compliance period (1,000 years)
- 10 • the protective assurance period (10,000 years)
- 11 • the performance period (site-specific values > 10,000 years)
- 12

13 The regulations specify individual dose limits (for the compliance period) rather than collective
14 dose to a population. A licensee should estimate the projected individual doses for the
15 performance period and the resources used to reduce those impacts to certain dose values or
16 the projected cost to achieve different dose values. Dose values that a licensee may consider
17 for comparison purposes may include the 10 CFR 61.41 public annual dose limit for the
18 compliance period (25 mrem/yr), the 10 CFR 61.42 intruder annual dose limit for the compliance
19 period (500 mrem/yr), the 10 CFR Part 20 public annual dose limit (100 mrem/yr), and
20 background radiation values for the site, or other limits for which a licensee provides technical
21 bases. Radiological doses at very long timeframes are based on many unstated
22 assumptions. However, radiological doses provide a present day metric for stakeholders to
23 consider. Other metrics may be appropriate for a licensee to consider, such as concentrations
24 in the environment and flux rates. The analyses should demonstrate that a reasonable attempt
25 has been made through site selection, facility design, and waste acceptance to minimize
26 releases to the public to extent reasonably achievable for the performance period (see Example
27 7.4).

28
29 In summary, the NRC staff recommended approach to performance period analyses entails the
30 following primary elements:

- 31
- 32 • A summary of present day resources, with no use of discounting, used to limit releases
33 for different regulatory timeframes
- 34 • A description of the additional resources needed to achieve a greater reduction in
35 releases during the performance period, or why further reductions are not possible
- 36 • A discussion of why additional resource usage is not warranted

37
38
39
40
41

Example 7.4: A disposal site is located in a semi-arid environment in an area of low-relief and long-term accretion. The waste streams proposed for disposal have a SOF of 4.3 when evaluated against the Table A concentrations in 10 CFR 61.13(e). Therefore, performance period analyses are required. Because the compliance period analyses demonstrated that the performance objectives would be met by a significant margin, the licensee elects to perform a screening analysis for the performance period by extending the compliance period calculations beyond the protective assurance period to the performance period with conservative parameters.

Conclusion: The licensee provides the regulator with a list of the potential radiation exposure pathways to the public. The dominant release pathway in the compliance period analysis was via ground water. It is anticipated that this may also be the dominant exposure pathway for the performance period analyses. The licensee performs an assessment of FEPs that were screened out of the compliance period assessment to determine if any of those phenomena are potentially significant to the performance period analyses. The only significant process identified is natural cycling of the climate. Because the site is located in the Southern US, the impact of natural cycling of climate is represented in the screening analyses by assuming a wetter and cooler climate (e.g., greater infiltration). Conservatism introduced in the screening analyses for the performance period include elimination of sorption during transport, assuming the engineered cover provides no reduction in natural recharge rates, and assuming the primarily carbon steel waste packages provide no barrier to release or transport. Because solubility limits were not applied in the compliance period analyses they are not adjusted for the performance period analyses. The receptor characteristics are adjusted to be consistent with the climate state.

The screening analyses for the performance period results in an estimated peak all pathways dose of 40 mrem/yr at 30,000 years. A sensitivity analysis on the long-term infiltration rates is included to address future climate state uncertainty. The licensee includes a comparison of the flux (g/yr) of naturally-occurring radionuclides from the disposal facility with those originating from natural sources, in a nearby river. The fluxes from the facility are less than those from natural sources.

The licensee also develops a cost comparison of some engineered alternatives to the disposal facility and how they could impact performance period doses. Only technologies that would result in a significant increase in cost or are unproven result in a significant decrease in projected impacts. Because the projected doses from the conservative screening analysis do not significantly exceed the compliance period dose limit, only a first-order assessment of technologies and their impacts is warranted.

The licensee performs barrier analyses to determine the most significant components of the system that are reducing releases. For the performance period, the licensee determines that dilution and dispersion during transport are very significant. In addition, solubility limits and sorption during transport could be very important, though they are not credited in the conservative screening analyses.

Because the compliance period scope was supplemented and conservatism was used in the analyses, the performance period analyses should be sufficient to demonstrate that releases for the performance period have been minimized to the extent practical even if the estimated doses exceed the compliance period dose limit.

1 **7.4.1.2 Barrier Analyses**

2
3 Licensees should use barrier analyses to identify and describe the capabilities of barriers, the
4 challenges and stresses expected to be imposed on barriers, and the contribution of barriers to
5 limiting or delaying releases of long-lived waste into the environment. Licensees can use
6 different types of analyses, ranging from qualitative to quantitative, to demonstrate how the
7 barriers of the disposal facility limit long-term impacts. Barrier and component analyses can be
8 used to satisfy 10 CFR 61.13(e) to illustrate the long-term performance of barriers and
9 components of an LLW disposal system. Barrier and component analyses involve decomposing
10 the performance of the system into the performance of the components under assumed
11 scenarios or configurations.

12
13 Licensees should provide a discussion of the capabilities of engineered and natural barriers to
14 reduce releases or exposures. The discussion can be useful for various stakeholders to
15 develop understanding of the disposal system performance. Events and processes that may
16 impact those capabilities should also be discussed. A discussion of the expected persistence
17 and durability of the barriers, and the basis for the expected durability, will be useful for many
18 stakeholders. At long timeframes, the performance of an engineered barrier is likely to be
19 diminished. A challenge with taking a qualitative approach to describing barrier performance is
20 determining the actual barrier performance rather than the potential barrier performance. The
21 potential barrier performance may not be realized because (1) the performance is deteriorated
22 or eliminated by processes and events, or (2) because the performance is masked by the
23 performance of other barriers, even though it is favorable to have independent, redundant
24 barriers (see Section 8.0). In addition, as-built performance can differ from as-designed
25 expectations. Quantification of the performance of the engineered and natural barriers is useful
26 because the estimated performance of the barrier is represented in the calculation regardless of
27 whether the performance is close to potential or has significantly deteriorated. Quantitative
28 barrier analyses can reduce some of the challenges and provide estimated performance based
29 on available information.

30
31 Semi-quantitative analyses may involve estimating the performance of individual components or
32 materials in the disposal system and providing the basis for the performance of the component
33 or material. For example, if a robust engineered cover using durable rock is provided for
34 erosion protection, estimation of the durability of the rock over the long-term may provide
35 confidence in future performance without detailed landform evolution modeling. Estimation of
36 the ages and stability of surrounding analogous landforms may be useful in providing inferential
37 information about the long-term stability of the waste disposal site.

38 Quantitative analyses, such as extension of technical analyses calculations from the compliance
39 period and protective assurance period to the performance period, can provide estimates of the
40 ability of the disposal system to limit long-term impacts, as long as the scope of the compliance
41 period and protective assurance analyses is sufficient for the performance period analyses.

42 **7.4.1.2.1 Methods**

43
44 Different methods are available to perform barrier and component analyses, including, but not
45 limited to, one-off analyses, one-on analyses, and factorial designs (Esh et al., 2001; NRC,
46 2004a, Eisenberg and Sagar, 2000). Typically, the term “one-off” analysis is used to refer to
47 varying one parameter — in this case, one barrier — at a time. Barrier and component

1 analyses are usually performed by isolating the performance of the particular barrier or
2 component. The biggest challenge in performing these analyses is usually communicating what
3 the results mean and how they should and should not be interpreted, because the calculations
4 provide a hypothetical situation that may never arise (e.g., elimination of a geologic unit, or
5 failure of all waste packages at a single instant).
6

7 Barrier and component analyses can be performed at different levels of resolution. Different
8 levels of resolution can provide important detail to help focus the regulatory review. For
9 example, representation of a disposal system as its components — an engineered cover,
10 disposal vaults, wasteform, unsaturated zone, and saturated zone — can convey broadly which
11 areas are contributing to performance in mitigating risks. Refinement of that analysis, such as
12 looking at individual layers in a multilayer engineered cover, may identify specific areas of
13 performance.
14

15 Barriers and components in the disposal system (e.g., engineered barriers and disposal site)
16 may reduce the magnitude of doses or change the timing of when doses could occur. The
17 barrier and component analyses look at changes to both the magnitude of projected doses and
18 the timing of when those doses are projected to occur. Some barriers may impact both metrics,
19 while others may only impact a single metric.
20

21 Environmental system models may include a range of coupling of components from weak to
22 strong. The licensee will need to clearly identify how processes that may affect multiple
23 components have been treated in the barrier and component analyses. In addition, disruptive
24 processes and events may impact multiple barriers or components. Disruptive processes and
25 events may be more important to consider during the performance period compared to the
26 compliance period or protective assurance period because of the longer time during which they
27 could occur. A licensee can perform barrier and component analyses after a disruptive event
28 has been assumed to occur, in order to understand how the components of the disturbed
29 system may be contributing to limit the impacts from the disruptive event.
30

31 One-off analyses are analyses in which the performance of a single barrier or component is
32 neglected in order to understand the contribution of the barrier to performance when the system
33 is operating under the anticipated range of conditions. Each barrier or component is analyzed in
34 this manner and the relative performance, such as the change in peak dose, is compared. For
35 example, the contribution of an engineered cover to performance could be evaluated by setting
36 the infiltration rate into the disposal system to a value that represents a natural recharge rate in
37 the region of the disposal facility. If the engineered cover had other contributions to
38 performance (e.g., reducing radon fluxes) those should also be eliminated in this type of
39 analysis. The results are best expressed on a relative basis, such as percent change, as the
40 analyses may be unphysical. But these types of barrier analyses calculations can have value
41 because they clearly convey which elements of the system are providing the most contribution
42 to performance, and therefore, which elements should have the most technical basis and most
43 rigorous review effort.
44

45 Individual components or barriers may have a redundant performance function with other
46 components or barriers. A one-off analysis result that indicates the performance did not change
47 when a component was “turned off” could represent that the barrier or component truly does not
48 contribute significantly to overall performance. However, the resulting lack of estimated
49 performance could indicate that a different barrier is providing a redundant functionality. A

1 licensee can use different analyses, such as one-on and factorial designs, to complement the
2 one-off type of barrier and component analyses to reveal this type of redundant functionality.

3
4 “One-on” analyses are analyses in which only a single barrier or component is represented in
5 order to determine the potential performance of the barrier. A benefit of the one-on analysis is
6 that it identifies the hypothetical maximum consequence that the waste could produce.
7 However, the usefulness of this type of analysis is reduced when the likelihood for the
8 hypothetical consequences becomes overly remote. One-on analyses can be useful in
9 identifying when different barriers may be providing redundant performance functions. A
10 disadvantage of one-on analyses is that they do not address the likelihood of the hypothetical
11 result ever being achieved. As long as it is understood that the purpose of the analyses is to
12 understand how barriers could contribute, misinterpretation of the results can be avoided. The
13 base case analysis, with all barriers and components present, represents the best estimate of
14 disposal system performance, assuming that the level of performance assigned has an
15 adequate technical basis.

16
17 A licensee can use factorial designs to provide a more complete picture of the contribution of
18 various barriers and components to the overall system performance. The factorial design is one
19 in which all combinations of barriers being “on” or “off” are generated. This type of analysis can
20 require significant resources, depending on the number of barriers and components in the
21 system being evaluated and the computational expense of the models being evaluated. When
22 a full factorial assessment is not practical, a licensee can consider a partial factorial
23 assessment. The compilation and interpretation of results from a factorial barrier assessment is
24 not straightforward. The relative change in performance will be much different depending on the
25 number of barriers or components that may be active in the calculation. One way to overcome
26 this problem is simply to rank the barrier contributions for each similar calculation. Example 7.5
27 provides additional detail on how this may be accomplished.

28
29 Barrier addition analysis is a process in which the hypothetical maximum consequence of the
30 waste is generated. After the licensee estimates the maximum consequence, barriers or
31 components can be added one by one until the full system is represented. A challenge with
32 barrier addition analyses is that the sequence in which the barriers are added may influence the
33 results prescribed to any one particular barrier. Barriers added early in the sequence are more
34 likely to show large performance benefits than barriers added later in the sequence.

35
36 In order for barrier and component analyses to be most useful, they should be carefully
37 performed by analysts that understand all of the components and barriers of the overall system
38 performance. The level of underperformance assigned to a barrier or component, which is
39 subjective, can influence the results and interpretation of the importance of that barrier or
40 component. The level of underperformance ascribed may represent both the amount of
41 degradation expected as well as pessimism in the estimate of performance. Licensees should
42 clearly explain the level of underperformance and, if possible, should assign this level of
43 underperformance based on the amount of confidence in the understanding of the performance
44 of the barrier or component. A barrier with a strong technical basis for its performance should
45 be much less likely to not perform than one for which the technical basis is weak or limited.
46 Although barrier and component analyses can provide useful information to understand how a
47 system may perform, the analyses may not provide a correct representation of how the system
48 is expected to perform.

1 7.4.1.2.2 *Design, Site, and Overall Performance*

2
3 Differentiation between barriers that are engineered (i.e., design) and those that are natural (i.e.,
4 site) classes or types can be useful in understanding overall performance and explaining to
5 stakeholders why the system is expected to protect public health and safety. Generally,
6 engineered components provide greater benefit at earlier times and natural system components
7 provide greater benefit at later times. The engineered design should be integrated into the
8 natural site, which can make a clear separation less obvious. In addition, the NRC staff expects
9 that natural system conditions will have a strong influence on the performance of the engineered
10 design. In some cases, the engineered design could influence the performance of the natural
11 system (e.g., leaching of cement that impacts sorption in the unsaturated zone or erosion of
12 surface soils at the toe of a slope). Engineering judgment can be used to classify barrier and
13 component types as long as the analysis is transparent and traceable. Classification is the
14 separation of the different barriers into classes based on the type of barrier (i.e., engineered or
15 natural). Some phenomena may be difficult to classify, for example the chemical environment
16 inside a waste container. The goal is to provide the classification that provides the clearest
17 understanding of overall system performance.

18

Example 7.5 – A disposal system has five primary barriers, #1 through #5. A factorial barrier assessment is completed. The simulations are as follows:

#1	#2	#3	#4	#5
off	on	on	on	on
on	off	on	on	on
on	on	off	on	on
on	on	on	off	on
on	on	on	on	off
off	off	on	on	on
off	on	off	on	on

[full matrix not shown]

off	off	off	on	off
off	off	off	off	on

An overall performance measure is generated by calculating the rank of the analysis result relative to the rest of the results of that class (i.e., analyses with the same number of components turned “on” or “off”), then generating the average rank over all classes.

For example the results for the one-off class are as follows:

#1	#2	#3	#4	#5
+5%	+30%	+1%	+200%	+17%

This results in the following ranks for the one-off class:

#1	#2	#3	#4	#5
4	2	5	1	3

The average change for each two-off combination is the following (any two-off that includes a #1 in the combination goes into the average change for #1):

#1	#2	#3	#4	#5
+57%	+89%	+132%	+310%	+37%

This results in the following ranks for the two-off classes:

#1	#2	#3	#4	#5
4	3	2	1	5

The average rank of each barrier averaged over each class provides a barrier importance measure:

#1	#2	#3	#4	#5
4	2.5	3.5	1	4

(average rank for each barrier)

8.0 DEFENSE-IN-DEPTH ANALYSES

The core of the NRC’s safety philosophy has long included the concept of defense-in-depth. The regulations at 10 CFR 61.2 define defense-in-depth as “the use of multiple, independent, and redundant layers of defense so that no single layer, no matter how robust, is exclusively relied upon”. The ultimate purpose of defense-in-depth is (1) to compensate for uncertainty in the type and magnitude of safety challenges, and (2) to compensate for uncertainty in the performance of the measures that are taken to ensure safety. Consistent with the NRC’s regulatory philosophy, the regulations at 10 CFR 61.13(f) require that land disposal LLW facilities demonstrate that defense-in-depth protections are included to provide reasonable assurance that the 10 CFR Part 61 performance objectives can be met.

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

Defense-in-depth protections are required by 10 CFR Part 61 to prevent, contain, or mitigate exposure to radioactive material according to the hazard present, the relevant scenarios, and the associated uncertainties. Defense-in-depth protections also ensure that the risks resulting from the failure of some or all of the established barriers and controls, including human errors, are maintained at an acceptably low level. These two aims help to provide reasonable assurance that the 10 CFR Part 61 performance objectives can be met, in light of the uncertainties in projecting the behavior of the land disposal facility over both the operational and post-closure periods.

To demonstrate that 10 CFR 61.13(f) is met, licensees should describe the layers of protection that ensure that the risks are properly managed. The description should identify the use of multiple layers of protection and describe how the various layers maintain independence and provide redundancy. The description of the layers of protection can be principally drawn from risk insights derived from the results of other 10 CFR Part 61.13 technical analyses (e.g., performance assessment, intruder assessment, stability analyses, and performance period analyses), although licensees may develop separate analyses for demonstrating defense-in-depth.

This chapter describes the information that a licensee should provide and a reviewer should evaluate with respect to demonstrating that a land disposal facility includes defense-in-depth protections. Sections 8.1 and 8.2 discuss NRC’s defense-in-depth philosophy and elaborate on key concepts of the defense-in-depth regulatory philosophy as they apply to LLW disposal facilities, respectively. Section 8.3 provides guidance on demonstrating defense-in-depth protections during the operational and post-closure phases of the land disposal facility lifecycle.

8.1 Background on Defense-in-Depth

Defense-in-depth is a regulatory philosophy or concept that has been used since at least the 1960s in the context of ensuring nuclear reactor safety. The philosophy is intended to deliver a

1 design that compensates for uncertainties in knowledge of facility behavior, component
2 reliability, or operator performance that might compromise safety.

3

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

17

recognized that complete reliance for safety cannot be

18 placed on any *single* element of the design, maintenance, or operation of a facility. The policy
19 statement highlighted the need for redundancy in active safety systems and a multiple barrier
20 approach to protect against releases. An essential property of defense-in-depth is the concept
21 of successive barriers or layers. These barriers or layers are commonly represented within the
22 NRC's regulatory framework in two different ways (Sorensen, et al., 1999). First, the NRC's
23 framework requires the use of high-level layers of protection, such as the prevention of accident
24 initiators, the quick termination of accident sequences, and the mitigation of accidents that are
25 not successfully terminated. Second, the NRC's framework requires the use of multiple physical
26 barriers, which are specified for particular facilities or material uses.

27
28 In 1999, the NRC's Staff Requirements Memorandum for SECY-98-144, "White Paper on Risk-
29 Informed and Performance-Based Regulation," approved descriptions of many terms including
30 defense-in-depth (NRC, 1999d). The SRM describes defense-in-depth as an element of the
31 NRC's safety philosophy that employs successive compensatory measures to prevent accidents
32 or mitigate damage if a malfunction, accident, or naturally caused event occurs at a nuclear
33 facility. The philosophy ensures that safety will not be wholly dependent on any single element
34 of the design, construction, maintenance, and operation of a nuclear facility. The net effect of
35 incorporating defense-in-depth into design, construction, maintenance, and operation is that the
36 facility or system in question tends to be more tolerant of failures, external challenges, and
37 uncertainty in the behavior of the facility.

38
39 More recently, in NUREG-2150, the NRC has characterized defense-in-depth protections as
40 part of the development of a holistic vision for all facilities regulated by the NRC, including land
41 disposal facilities (NRC, 2012c). The NRC's risk-informed, performance-based characterization
42 indicates that defense-in-depth protections (1) ensure appropriate barriers, controls, and
43 personnel prevent, contain, and mitigate exposure to radioactive material according to the
44 hazard present, the relevant receptor scenarios, and the associated uncertainties; and (2)
45 ensure that the risks resulting from the failure of some or all of the established barriers and
46 controls, including human errors, are maintained acceptably low.

47
48 As stated above, the regulations in 10 CFR Part 61.13 (f) require licensees to explicitly describe
49 how the proposed disposal facility includes defense-in-depth protections. The regulations in

1 10 CFR Part 61 also implicitly incorporate the concept of defense-in-depth into the regulatory
2 framework. Implicit defense-in-depth provisions of the regulations include multiple performance
3 objectives, as well as requirements for site suitability, site design, facility operation, site closure,
4 environmental monitoring, waste acceptance, land ownership and institutional control, and
5 financial assurance.

6 **8.2 Defense-in-Depth Concepts for a Land Disposal Facility**

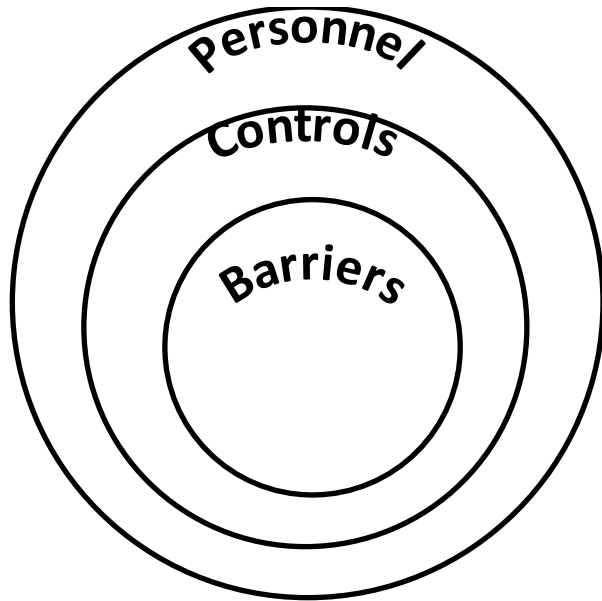
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8 The NRC's use of the defense-in-depth philosophy is intended to deliver a design that is can
9 handle uncertainties in knowledge of facility behavior, component reliability, or operator
10 performance that might compromise safety. While justifiably important for nuclear facilities with
11 large potential risks, it is similarly important for land disposal facilities for radioactive wastes,
12 which can contain relatively large radiological hazards. Disposal facilities, being the endpoint of
13 the nuclear fuel cycle, are responsible for containing and isolating the radioactivity for time
14 periods far into the future. As with any estimation far into the future, uncertainty grows the
15 farther out in time one attempts to estimate future performance as the system moves away from
16 what is known today. The use of defense-in-depth protections is, therefore, a prudent approach
17 to managing the uncertainty associated with estimating performance far into the future to ensure
18 the safe disposal of radioactive wastes.

19
20 As identified in the definition of defense-in-depth at 10 CFR Part 61.2, the philosophy relies
21 upon multiple, independent, and redundant layers of defense so that no single layer, no matter
22 how robust, is exclusively relied upon. Multiple layers provide confidence that if an individual
23 layer fails or underperforms, other layers of defense would be available to protect health and
24 safety and the environment. Redundant layers provide confidence that should an individual
25 layer fail or underperform, another layer will be available to provide similar capabilities as the
26 individual layer to protect health and safety and the environment. Independent layers enhance
27 confidence that the layers of defense are less likely to fail or underperform by common-cause
28 modes in which a single event or process is able to defeat or diminish the capabilities of each
29 layer simultaneously. In the end, multiple, independent, and redundant layers are intended to
30 provide a margin of safety to account for uncertainty in the evolution of the land disposal facility
31 over time. The margin of safety needed is dependent upon the hazard presented by the waste
32 emplaced in the land disposal facility and ultimately by the potential risk of harm to health and
33 safety and the environment. The different types of layers complement each other and when
34 used together develop a more comprehensive approach to defense-in depth protections.

35 **8.2.1 Multiple Layers**

36
37 Multiple layers of defense provide confidence (1) that accidents can be prevented, (2) that the
38 effects of an accident can be lessened should a malfunction or accident occur, and (3) that
39 there is adequate protection should a layer of defense underperform due to uncertainty in its
40 expected behavior. Reliance on multiple layers of defense ensures safety will not be wholly
41 dependent upon any single element of the design, construction, maintenance, or operation of
42 the land disposal facility. Multiple layers of protection use numerous, diverse protection
43 mechanisms or actions to ensure safety. Layers of defense can consist of a number of
44 attributes including physical or chemical barriers to radionuclide release, appropriate controls
45 that help ensure the physical barriers perform as intended, and trained and qualified personnel
46 who are focused on safety (see Figure 8-1).

47



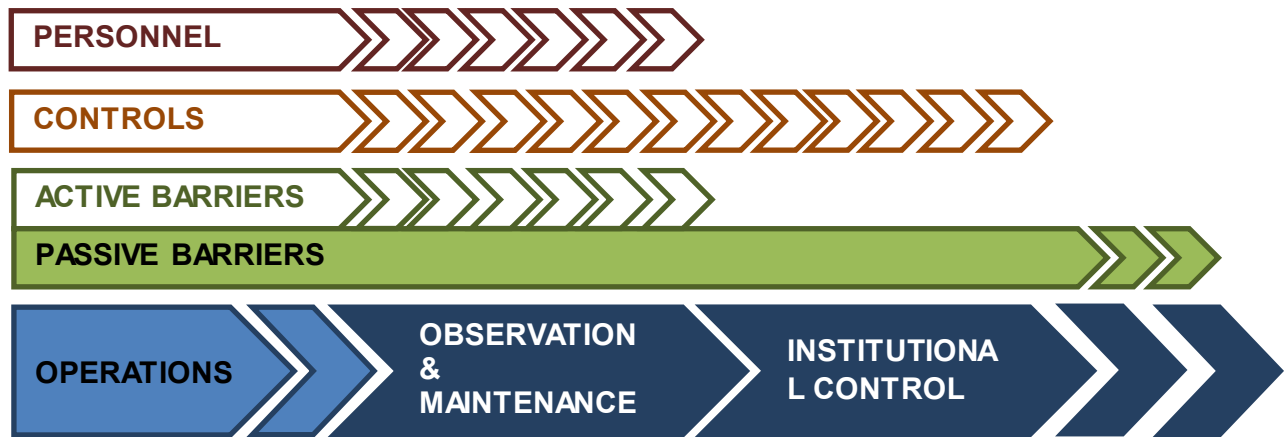
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Figure 8-1 Multiple Layers of Defense

Each of the layers has an associated capability or safety function that is intended to mitigate releases and exposures to workers and the public during both normal operations and accidents. The function performed by an individual layer may be active, passive, or in some cases, a layer may provide both active and passive safety functions. Active safety functions are those that require activity or energy by the licensee to monitor and maintain protection. For example, an air filtration system requires continual maintenance, as well as an available energy source to ensure that its functionality to remove radioactive particulates is available when needed. Passive safety functions do not require ongoing activity or external energy inputs from the licensee to provide protection. For instance, a wasteform, once created, typically would not require ongoing maintenance to perform its safety function (i.e., limit the release of radionuclides), though its safety function would likely degrade over time. The role of barriers, controls, personnel, and their associated safety functions in demonstrating defense-in-depth for a land disposal facility are discussed in more detail below. For land disposal of LLW, passive layers of defense are more appropriate for the post-closure period because they do not require ongoing maintenance and monitoring. Active layers of protection are more appropriate during the operational period.

When identifying barriers, controls, or personnel relied upon for safety, licensees should clearly describe the functionality or capability provided by the barrier, control, or personnel to achieve the performance objectives and provide defense-in-depth protections. The description of the safety function should include a technical basis for the function and associated uncertainty in the function of the barrier, control, or personnel. In some cases, the safety function may only be necessary for a specific timeframe. For example, a licensee identifies a waste container as a barrier to waste release for short-lived radionuclides. The licensee should specify the time period over which the safety function provided by the waste container is necessary to demonstrate that the performance objectives are met and defense-in-depth protections are

1 provided. Figure 8-2 depicts approximate time periods over which safety functions for barriers,
2 controls, and personnel may be appropriate.
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Figure 8-2 Land Disposal Facility Lifecycle and Timeframes for Defense-in-Depth Layers (Duration of lifecycle timeframes are not to scale. Dark blue timeframes are considered the post-closure period.)

8.2.1.1 Barriers

For the land disposal of LLW, barriers can take a number of forms, such as a container, a wasteform, a wall, or a restricted area of land. Barriers can be either engineered or natural. Barriers are intended to improve the land disposal facility's ability to meet the 10 CFR Part 61 performance objectives and add to defense-in-depth. In the context of disposal, barrier safety functions, which are also described as barrier capabilities, are typically intended (1) to prevent or limit the contact of water with the waste, (2) to limit the release or rate of release of radioactivity from the waste, or (3) to prevent or limit biotic contact with the waste (for inadvertent intrusion). For normal operations and abnormal events (e.g., accidents), barrier safety functions are typically designed to prevent, contain, and mitigate exposure to radioactive material.

Engineered barriers at LLW disposal facilities are generally man-made features that are designed to mitigate the effect natural processes could have on the performance of the disposal facility and also limit human activities that may expose individuals to radiation or initiate or accelerate release of radioactivity from the waste through environmental pathways. The intent of engineered barriers is to improve the land disposal facility's ability to meet the performance objectives in 10 CFR Part 61 and add to the defense-in-depth provided by the facility design and construction. Examples of engineered barriers include (1) closure caps, which are designed to limit infiltration into disposal units, and (2) waste containers and wasteforms, which may provide shielding to site workers during emplacement and preclude or limit the release of radionuclides from the disposal units once emplaced.

Natural barriers are generally barriers inherent to the disposal site that limit exposures to the waste. Examples of natural barriers include the climatic or the hydrogeologic layers of the disposal site. Limited infiltration associated with an arid climate may result in long travel times

1 of radionuclides from the waste to underlying groundwater. Likewise, hydrogeological layers
2 may retard the movement of radionuclides from the disposal site as a result of sorption
3 processes.

4 **8.2.1.2 Controls**

5
6 A control can be an apparatus or mechanism that, through its manipulation or administration,
7 serves to protect public health and safety and the environment around the land disposal facility.
8 During operations, controls are intended to prevent, contain, and mitigate exposure to
9 radioactive material at or in the vicinity of the land disposal facility. Operators also employ
10 controls to ensure the performance of barriers during either the operational period or after
11 closure of the land disposal facility.

12
13 Controls can largely be classified as either engineering or administrative controls. Engineering
14 controls include any man-made apparatus that is designed to ensure the performance of a
15 barrier or provide a level of protection independent of a barrier. For example, an engineering
16 control may include something as simple as a visible or audible alarm as part of access control
17 to restricted areas or more complex systems such as a fire alarm and suppression system to
18 limit the damage from a potential fire. Administrative controls encompass a wide array of
19 managerial mechanisms. Administrative controls include provisions related to organization and
20 management, procedures, record keeping, material control and accounting, waste acceptance,
21 and management review. Administrative controls can also include legal mechanisms such as
22 land ownership, as required by 10 CFR 61.59(a).

23 **8.2.1.3 Personnel**

24
25 Properly trained and qualified personnel are necessary to ensure proper design, installation,
26 operation, or administration of barriers and controls that prevent, contain, or mitigate exposure
27 to radioactive materials. Properly trained and qualified personnel also ensure that human errors
28 that can lead to failure of some or all of the established barriers and controls are maintained
29 acceptably low and safety is maintained. Personnel may also be able to mitigate exposures in
30 an accident. For example, properly trained emergency responders can mitigate potential
31 releases of radioactivity from the land disposal facility in the case of an accident or an
32 emergency. Because reliance on personnel inherently relies upon activity, personnel always
33 provide active safety functions. Designated personnel may be an appropriate layer of protection
34 during operations; however, the regulations at 10 CFR Part 61 intend that active maintenance
35 and monitoring of the site after closure is not relied upon for safety. Therefore, the reliance on
36 personnel for defense-in-depth protections after closure is not appropriate.

37 **8.2.2 Independent Layers**

38
39 In addition to multiple layers of protection, which are discussed in Section 8.2.1, the definition of
40 defense-in-depth specified in 10 CFR Part 61 requires that the land disposal facility incorporate
41 independent layers of protection. Independence applies to the safety function in that a given
42 layer should provide a safety function that is not dependent upon other layers of defense to
43 perform their respective safety function. For instance, a licensee may use an engineered
44 closure cap as one barrier to limit the flow rate of water contacting the waste and an engineered
45 wasteform as another barrier to limit the solubility of certain radionuclides in water contacting
46 the waste. If the closure cap were to fail, resulting in a higher flow rate of water into the disposal

1 unit, the wastefrom would still be expected to maintain low concentrations of solubility-limited
2 radionuclides in the water leaving the disposal units. In some cases, multiple layers of defense
3 may appear to be independent, but the safety functions performed by each layer may actually
4 be dependent. For example, a land disposal facility may dispose of waste in a metallic waste
5 container whose safety functions are to limit the contact of water with the wastefrom and release
6 of radionuclides. In addition, the facility disposes of the waste in a metallic wastefrom that is
7 also relied upon to limit the release of radionuclides. The waste container and wastefrom may
8 appear to provide independent functionality; however, certain chemical environments could
9 cause degradation to both the waste container and waste form simultaneously. Further, the
10 degradation of the waste container may directly result in more rapid degradation of the
11 wastefrom, resulting in a dependency between the waste container and wastefrom to limit
12 releases of radionuclides from a disposal unit.

13 **8.2.3 Redundant Layers**

14
15 In addition to the multiple and independent layers of protection discussed above, the definition
16 of defense-in-depth specified in 10 CFR Part 61 requires that the land disposal facility
17 incorporate redundant layers of protection. The use of redundant layers increases confidence
18 that safety is not reliant upon any single layer. Redundancy is the duplication of layers of
19 defense, in order to prevent the failure of the entire disposal system if a single item or
20 component relied upon for safety fails or provides a safety function that is less than expected.
21 Licensees should demonstrate that the land disposal facility has redundancy for key functions
22 relied upon for safety.
23

24 Redundancy goes beyond implementing multiple layers. Redundancy requires that the safety
25 function performed by a layer be duplicated or even triplicated or more for safety-critical
26 components in high-risk scenarios. The duplication of a safety function may occur within the
27 same layer (e.g., as a redundant component) or in other layers incorporated into the siting,
28 design, construction, maintenance, or operation of the disposal facility. For instance, different
29 stratigraphic units beneath a disposal facility may each sufficiently retard the migration of key
30 radionuclides, thereby, providing redundancy should the licensee's understanding of the primary
31 unit's sorptive capabilities prove incorrect. In this example, licensees would also need to
32 provide reasonable assurance that groundwater flow occurs through the stratigraphic units and
33 that preferential flow pathways that could minimize the water contact with the stratigraphic units
34 would not be limited.

35 **8.2.4 Safety Margin**

36
37 Safety margin is the excess functionality remaining to provide safety after the demands of a
38 particular scenario are placed on the functionality of the layer or system. In some high-risk
39 scenarios, additional controls on the safety functions of a layer may be necessary in order to
40 ensure an adequate safety margin. For instance, licensees may impose a design requirement
41 on an engineered barrier that provides confidence that the barrier's capability exceeds the
42 demand imposed by the scenario (e.g., by using a pre-determined safety factor). This excess
43 capability would provide greater confidence that safe conditions are maintained during normal
44 operations in light of uncertainties or in the event of abnormal occurrences, accidents, or
45 disruptive events. Conversely, licensees may overestimate the demands imposed by a
46 scenario when determining the required safety function needed from the layer of defense. The
47 concept of the safety margin is to ensure that safety functions are sufficient to account for

1 uncertainty in the characterization of the demands, as well as the robustness of the functionality.
2 Safety margins can be determined for an individual layer or the entire disposal facility, but the
3 margin for the disposal facility should be the primary interest for licensees and regulators.
4

5 Meeting the performance objectives, as demonstrated by the other 10 CFR 61.13 technical
6 analyses, demonstrates a level of safety margin for a LLW disposal facility because the dose
7 limits established in the performance objectives are purposefully established below the public
8 dose limit specified in 10 CFR Part 20 (to account for the possibility of exposure from multiple
9 facilities). Understanding the safety margin for abnormal occurrences, accidents, or disruptive
10 events is important to provide confidence that the performance objectives can be met, even if
11 less likely, but plausible, scenarios occur. Because abnormal occurrences, accidents, and
12 disruptive events are plausible, but generally less likely, licensees may account for the likelihood
13 of these events or processes occurring to determine the expected safety margin. For the post-
14 closure periods that are concerned with projected consequences, the licensee should
15 demonstrate that for plausible abnormal occurrences, accidents, or disruptive events the
16 potential doses would remain below those for which intervention would be necessary if they
17 were to occur today. Guidance on these levels is discussed in more detail in Section 8.3.3.2
18 for each post-closure period. Section 2.5.4 discusses the terms used to describe scenarios to be
19 included in technical analyses (i.e., reasonably foreseeable, less likely, but plausible, and
20 implausible). These terms and types of scenarios can also be used to demonstrate defense-in-
21 depth protections.

22 **8.2.5 Risk-Informed Approach**

23
24 Defense-in-depth should be applied in a risk-informed manner. As the hazard from the waste
25 increases, more robust layers of protection may be needed to account for uncertainty in the
26 performance of the barriers, controls, and personnel used to maintain safety. Alternatively, less
27 robust layers of defense may make additional redundancy necessary, depending upon the
28 uncertainty in the safety functions provided by the layer(s) and the risk posed by the waste. The
29 timeframe that the safety functions are provided by the layers of protection should be
30 appropriate for the time period over which significant risks are presented by the waste. Also, as
31 uncertainty in the functionality and reliability of barriers, controls, or personnel grows, additional
32 layers of protection may be needed to provide confidence that safety can be maintained. For
33 instance, for significant concentrations of long-lived waste, additional layers of protection may
34 be needed to account for the uncertainty associated with projecting performance over very long
35 time periods. Whereas, for shorter-lived hazards, fewer layers of protection or layers that
36 provide safety functions confidently over an appropriate time period may be sufficient.

37 **8.3 Defense-in-Depth Analyses**

38
39 The regulations at 10 CFR 61.13(f) require licensees to demonstrate that defense-in-depth
40 protections are provided for the land disposal facility. The licensee must demonstrate that
41 defense-in-depth protections are provided and should be performed in the context of the
42 Subpart C performance objectives, namely protection of the general population, protection of
43 inadvertent intruders, protection of individuals during operations, and stability of the disposal site
44 after closure. Therefore, licensees should demonstrate in a risk-informed manner that multiple,
45 independent, and redundant layers of defense are included in the disposal system to provide
46 confidence that no single layer will be exclusively relied upon. Demonstrating defense-in-depth
47 also provides greater confidence that each of the performance objectives can be met. In

1 providing layers of defense, licensees should consider the risks posed by the waste. Therefore,
2 more layers or more robust layers may be needed for demonstrating safety will be maintained
3 for higher risk scenarios. This section describes the role of defense-in-depth analysis required
4 by 10 CFR Part 61 and acceptable approaches licensees may take to demonstrate that
5 defense-in-depth protections are provided.
6

7 At a minimum, licensees should identify the defense-in-depth protections, describe the safety
8 functions the protections perform, provide a technical basis for the safety function provided by
9 each protection, and estimate the margin available to maintain safety. As described in Section
10 2.3 of this guidance, licensees should identify the regulatory requirement to demonstrate that
11 defense-in-depth protections are included at the land disposal facility as part of the assessment
12 context process. Thus, the defense-in-depth protections will typically be represented in the
13 system description (see Section 2.4) and modeled in one or more of the 10 CFR 61.13(a)
14 through (e) technical analyses, such as the performance assessment or intruder assessment, in
15 order to demonstrate that the performance objectives will be met. Therefore, licensees should
16 be able to draw, principally, upon the results and risk insights gained from those other analyses
17 to identify and describe defense-in-depth protections at the land disposal facility rather than
18 developing separate analyses for demonstrating defense-in-depth.
19

20 In some cases, licensees may need to consider whether additional features, events, and
21 processes or alternative scenarios might be appropriate to consider solely for demonstrating
22 that defense-in-depth protections are included (see Section 2.5). For example, a licensee may
23 not expect a certain scenario to be reasonably foreseeable for the purposes of demonstrating
24 that the performance objectives are met and would therefore not include such a scenario in the
25 demonstration. However, for the purpose of demonstrating that adequate defense-in-depth
26 protections are provided, the licensee should consider the less likely, but plausible scenario.
27 Licensees would not need to consider scenarios that are sufficiently unlikely and can be
28 considered implausible.

29 **8.3.1 Identification of Defense-in-Depth Protections**

30
31 Licensees should identify the defense-in-depth protections that are included at the land disposal
32 facility. The identification of these protections, or layers of defense, should demonstrate that
33 multiple barriers, controls or personnel are used at the land disposal facility. Section 8.2.1
34 provides descriptions of barriers, controls, and personnel in the context of defense-in-depth
35 protections for a land disposal facility. Licensees should also clearly indicate when layers are
36 included for redundancy.
37

38 The specific defense-in-depth protections for the operational versus the post-closure time
39 periods are likely to be different because active maintenance of the site after closure is not
40 anticipated. Following closure of the land disposal facility, defense-in-depth protections shift
41 from a collection of active and passive barriers and controls that are used during operations to
42 reliance on more passive barriers and controls to provide reasonable assurance that the
43 performance objectives will be met for timeframes far into the future. This shift is necessary
44 because the regulations at 10 CFR Part 61 specify that active maintenance of the disposal site
45 beyond monitoring, surveillance, and minor custodial activities cannot be relied upon after the
46 period of post-closure observation and maintenance, and without ongoing maintenance, active
47 barriers and controls cannot be relied upon indefinitely. Defense-in-depth protections for the
48 post-closure period may include, but are not limited to, engineered features (e.g., closure caps,

1 wasteforms, and containers) and natural characteristics (e.g., hydrogeology) of the disposal site
2 that are intended to contain and isolate the waste, as well as controls such as institutional
3 controls, which are designed to limit access to the disposal site for a limited period of time, and
4 waste acceptance requirements, which are designed to limit the radionuclide inventory in the
5 disposal site.
6

7 The identification should be generally consistent with the key barriers, controls, or personnel
8 relied upon in the other 10 CFR 61.13 technical analyses. In some cases, the layers identified
9 to describe defense-in-depth may not be represented in the other 10 CFR 61.13 analyses. This
10 may often be the case for personnel identified as a defense-in-depth protection. In these cases,
11 licensees should provide a basis for identifying the layer as a defense-in-depth protection. In
12 other cases, there may be less significant barriers, controls, or personnel that provide
13 demonstrable safety functions in the other 10 CFR 61.13 technical analyses. If more significant
14 layers of defense provide multiple layers that can be shown to be sufficiently independent and
15 redundant, licensees would not need to identify the less significant layers as demonstrated by
16 the other 10 CFR 61.13 analyses. In other words, a licensee does not need to identify a
17 comprehensive list of layers of defense. Rather, a licensee only needs to identify that there are
18 multiple, independent, and redundant layers of defense, so that no single layer is exclusively
19 relied upon for safety.
20

21 As part of the identification, licensees should also identify which layers of defense are included
22 for redundancy. Licensees should identify the primary layer and any associated redundant
23 layers that are expected to be relied upon in the event the primary layer degrades or fails early.
24 Licensees may associate a secondary layer as a redundancy for multiple primary layers and do
25 not need to limit the association of a redundant layer with a single primary layer. In some
26 cases, multiple layers can provide redundancy without subordinating one of the layers in the
27 identification. The classification of primary versus secondary in this case may be in name only.
28

29 Reviewers should confirm that the licensee has identified multiple layers of defense. While
30 licensees do not need to identify a comprehensive list, reviewers should confirm that the layers
31 of defense identified by the licensee are generally consistent with the layers represented in the
32 other 10 CFR 61.13 technical analyses. As part of this confirmation, reviewers should evaluate
33 whether the most significant barriers, controls, or personnel that are relied upon for meeting the
34 performance objectives are identified as defense-in-depth protections.
35

36 Reviewers should also confirm that the licensee has identified at least one redundant and one
37 independent layer of defense, though there may be different layers that provide the redundancy
38 and independence. Reviewers should confirm that the identification clearly associates a
39 redundant layer with each primary layer of defense. A single layer may be able to perform a
40 safety function that is redundant to several primary layers. As discussed in the next section, the
41 safety function provided by the redundant layer would need to be comparable, but not identical,
42 to the safety function provided by the primary layer and that often the designations of primary
43 and secondary, or redundant, layers are in name only for the purposes of identification.
44 Reviewers should also confirm that the licensee has identified which layers ensure
45 independence. Independence should be assured for the disposal site as a whole. In other
46 words, sufficient independence is demonstrated when common-cause failure scenarios are
47 implausible or result in consequences that are acceptable. The next section also provides
48 guidance on ensuring the safety functions for each independent layer are not subject to
49 common-cause failures.

8.3.2 Description of Safety Functions

Licensees should describe the safety function(s) provided by each layer that is identified as a defense-in-depth protection for 10 CFR 61.13(f). Licensees should either qualitatively or quantitatively describe the capability of the individual layers identified to maintain safety. In addition, the description should include a technical basis supporting for the safety function. In general the technical basis supporting the safety function can be drawn from the technical basis used to support the layer's representation in the other 10 CFR 61.13 analyses. General guidance on developing support for the technical analyses is provided in Section 2.2, and specific guidance for each of the other 10 CFR 61.13 analyses is provided in their respective sections of this document.

Often, for a land disposal facility, the safety functions focus on (1) limiting the contact of water or individuals with the waste, (2) minimizing the release of radionuclides from the waste, or (3) minimizing the rate of radionuclide transport through the site environment. In addition, safety functions cover other considerations such as maintaining structural stability or limiting exposures to radioactivity. The safety function(s) may vary depending upon which performance objective the layer of defense is focused. In addition, a layer of defense may provide more than one safety function and these different safety functions may be aimed at providing confidence that different performance objectives will be met. Thus, licensees should clearly identify the capabilities the layer performs and the performance objective(s) the safety function is focused on in their description of the safety function for an individual layer.

If a layer of defense is included for redundancy, the licensee should clearly indicate other layers of defense the redundant layer is intended to support. Also, licensees should describe whether the safety function is independent or dependent upon the safety functions of other layers. If a layer's safety function is dependent upon another layer, the licensee should identify the other layer(s) in each layer's safety function description. If a layer's safety function is independent of other layers' safety functions, the licensee should provide justification that reasonably foreseeable and plausible common-cause failure scenarios would not result in significant consequences should they occur. Alternatively, licensees could identify additional layers of defense which would render the likelihood of the common-cause failure scenario as implausible.

Licensees should ensure that the description of the safety function is consistent with the representation of the layer of defense in the other 10 CFR 61.13 analyses. For instance, if a waste container is identified as a layer of defense aimed toward providing confidence that the performance objective for protection of the general population can be met, the description of its safety function should be consistent with its representation in the performance assessment. If the waste container is relied upon to limit water contacting waste and were to be modeled as degrading over time in the performance assessment, the licensee should identify the degradation of its safety function as part of the description for defense-in-depth.

In some cases, layers of defense may not be amenable to representation in one of the other 10 CFR 61.13 analyses. For instance, representing the response of personnel to an emergency such as a fire may not be amenable to representation in one of the other 10 CFR 61.13 analyses because the behavior of the personnel may vary depending upon the specific circumstance of the fire and would be difficult to simulate. In these cases, licensees would need to document the safety functions performed by the layers for demonstrating defense-in-depth.

1 For the emergency personnel example, this may include written procedures for training and
2 emergency response, staffing plans, or agreements with local emergency responders.
3

4 Each layer of defense is likely to have a time period over which it will be designed to perform its
5 intended safety function. For instance, the safety functions of engineered barriers would
6 typically be expected to degrade and fail at some point in the future. However, some site
7 characteristics may continue to provide safety functions indefinitely. The licensee should
8 describe and justify this time period in its technical basis supporting the safety function of the
9 layer. If the time period over which the layer is intended to perform its safety function
10 significantly exceeds relevant experience, the licensee should provide additional support that
11 the layer will likely achieve its goal. Additional support could include the use of additional
12 redundant layers of defense, though support would be needed that the principal layer and any
13 redundant layers in combination would perform the safety function over the intended time
14 period.
15

16 Licensees should also describe the uncertainty in each layer's ability to perform its intended
17 safety function and the time period over which it is expected to perform. The description of the
18 uncertainty may be either qualitative or quantitative. The description of the uncertainty should
19 be generally consistent with the layer's representation in the other 10 CFR 61.13 analyses. In
20 describing the uncertainty associated with the safety function of a barrier, control, or personnel,
21 licensees should identify heterogeneity and variability in the behavior or reliability of the barrier,
22 control, or personnel as well as challenges to the functionality provided by a barrier, control, or
23 personnel that result from plausible scenarios. Challenges should include both reasonably
24 foreseeable scenarios expected during normal operations as well as less likely but plausible
25 scenarios such as abnormal conditions, accidents, or disruptive events.
26

27 Reviewers should evaluate the description of the safety function of each layer to ensure that it
28 clearly describes how the layer provides defense-in-depth protections and which performance
29 objective the safety function supports. Reviewers should also confirm the description includes
30 whether the safety function is included for redundancy, and whether the safety function is
31 independent of or dependent upon another layer's safety function.
32

33 Reviewers should confirm that the safety function for a layer identified as redundant is clearly
34 linked to the layer it is intended to support. Reviewers should confirm that the redundant layer's
35 safety function provides a comparable capability to the primary layer's safety function. In some
36 cases redundant layers that are identical to the primary layer are not possible. However,
37 licensees could identify another barrier that may provide a comparable safety function.

38 Reviewers should confirm that the safety functions are comparable. For instance, different
39 hydrostratigraphic layers of the site may provide similar, but not identical safety functions.
40 Likewise, an engineered barrier, such as a permeable reactive barrier, and a hydrostratigraphic
41 layer of the site may both retard the movement of radionuclides as their safety functions. In this
42 example, the safety functions are similar but the layers are not identical.
43

44 In addition to evaluating the licensee's basis for a redundant safety function, reviewers should
45 also evaluate whether the layers identified as independent are subject to common-cause
46 failures based on reasonably foreseeable as well as less likely, but plausible scenarios.
47 Plausible common-cause failures may result from a common initiating event such as a seismic
48 event that fails two barriers simultaneously. Plausible common-cause failures may also result
49 from a cascade of processes such as when a geochemical environment leads to the

1 degradation of a barrier whose degradation produces an environment that leads to the
2 degradation of a different barrier, which may not have been affected by the initial aggressive
3 environment.

4
5 Reviewers should also confirm the licensee's safety function descriptions include a discussion
6 of the time period over which the layer's safety function is intended to perform and the
7 uncertainty in whether the layer can perform the safety function. For layers of defense which
8 are expected to perform for time periods that significantly exceed relevant experience, reviewers
9 should confirm that the licensee has provided sufficient justification. Reviewers should also
10 coordinate the review of the safety function descriptions with reviews of the other 10 CFR 61.13
11 analyses to ensure that the layers and their safety functions are implemented in those other
12 analyses consistent with the licensee's description of the safety function for defense-in-depth. If
13 redundant layers are expected to perform over different time periods than the primary layers,
14 reviewers should confirm that the licensee has identified other layers to ensure that redundancy
15 is provided for the entire time period of interest or that the consequences would remain
16 acceptable should redundancy not be possible for the entire time period of interest.

17
18 Reviewers should also confirm the licensee has included a description of the uncertainty in each
19 layer's ability to perform its intended safety function and the time period over which it is
20 expected to perform as part of the safety function description. Reviewers should coordinate
21 their review of the description of uncertainty with the reviews of the other 10 CFR 61.13
22 analyses to ensure that the uncertainty descriptions are generally consistent and describe the
23 heterogeneity and variability in the behavior or reliability of the barrier, control, or personnel as
24 well as challenges to the functionality provided by a barrier, control, or personnel that result from
25 plausible scenarios.

26 **8.3.3 Demonstrating Safety Margin**

27
28 After describing the safety function provided by each layer identified as a defense-in-depth
29 protection, licensees should demonstrate that the layers will maintain safety and that no single
30 layer will be relied upon exclusively for safety. The level of detail provided by the licensee in
31 describing the technical basis should be risk-informed. Namely, for layers of defense that
32 provide one or more significant safety functions, licensees should provide a more detailed
33 description of the basis for the safety function provided by the layer of defense.

34
35 Licensees can use a variety of methods to demonstrate that safety functions will perform
36 adequately and that no single layer will be relied upon for safety in light of the uncertainties in
37 the performance of the layers and the evolution of the disposal site over long periods of time
38 such as those associated with the post-closure period. Generally, the methods may be
39 quantitative, qualitative, or a combination of the two approaches. Quantitative approaches
40 attempt to assign numerical values to the safety functions and the resulting safety margin
41 provided by the layers of defense relied upon for safety. Qualitative approaches are less
42 numerical and narratively describe the safety functions and the resulting safety margin of the
43 various layers of defense relied upon for safety.

44
45 Licensees may use different approaches to demonstrate layers of defense for different stages or
46 even within a stage of the land disposal facility's lifecycle. For instance, while some layers of
47 defense used during operations may be amenable to quantification other layers of defense may
48 not be, such as the safety margin provided by an emergency response plan to mitigate the

1 consequences of an accident. Typically, licensees should be able to use the results of the other
2 10 CFR 61.13 analyses to demonstrate that the layers will ensure the performance objectives
3 are met for reasonably foreseeable scenarios and that the consequences from less likely but
4 plausible scenarios would not be so large to require intervention if they were to occur today. For
5 instance, for the post-closure period, licensees should draw risk insights from the performance
6 assessment (see Section 3.0), intruder assessment (see Section 4.0), and site-stability analyses
7 (see Section 5.0) to demonstrate that no single layer is relied upon exclusively for safety over
8 the various time periods.

9
10 Rather than developing new analyses, licensees may use uncertainty analyses conducted for
11 the other 10 CFR 61.13 analyses such as barrier analyses, including one-off or what-if types of
12 analyses, to demonstrate adequate independence and redundancy is provided and that no
13 single layer is relied upon for safety for both reasonably foreseeable and less likely, but
14 plausible scenarios over the time period of interest. The results of these uncertainty analyses
15 can be used to demonstrate that if any single barrier fails during the time period of interest,
16 another barrier is available to provide a similar and adequate level of protection. The results of
17 the other 10 CFR 61.13 analyses can also be used to demonstrate that common-cause failures
18 would not result from reasonably foreseeable or less likely, but plausible scenarios or if
19 common-cause failure were to occur for plausible scenarios, the consequences would not be so
20 large as to require intervention today. Barrier analyses are described in more detail in
21 Section 7.4 for analyses for long-lived waste. Although the description in Section 7.4 relates to
22 performance period analyses, the barrier analysis techniques are also generally appropriate for
23 any of the post-closure time periods of interest. Consequences that may require intervention
24 today are discussed in the following sections for each time period with due consideration for the
25 uncertainty associated with projecting safety functions, human activities, and the behavior of the
26 disposal site environment far into the future.

27
28 The lifecycle of a land disposal facility can be divided into two broad phases: the operational
29 phase and the post-closure phase. The operational phase is the time period during which the
30 facility is being constructed, is receiving waste for disposal, or is preparing for closure. The
31 post-closure phase extends from the cessation of operations far into the future depending upon
32 the type of waste accepted for disposal. At a minimum the post-closure phase would include
33 the compliance and protective assurance periods. For facilities disposing of significant
34 quantities of long-lived waste, the post-closure phase would also include the performance
35 period. Because of the differences in length of the time periods for the operational and post-
36 closure phases, the role of defense-in-depth analyses may be markedly different for
37 each phase.

38
39 The following two sections describe considerations for licensees and reviewers for the two
40 major lifecycle phases of a land disposal facility and guidance on demonstrating a land disposal
41 facility's safety margin provided by the defense-in-depth protections and demonstrating that no
42 single layer, not matter how robust, will be exclusively relied upon for safety.

43 **8.3.3.1 Operational Period**

44
45 During the operational phase of the land disposal facility, defense-in-depth protections may be
46 similar to those used at other nuclear facilities that present similar hazards. Defense-in-depth
47 protections during operations may include, but are not limited to: (1) the selection and use of
48 facility capabilities, such as functions, structures, systems, and components of the facility

1 design; (2) programmatic processes, such as decisions regarding the processes of constructing,
2 operating, maintaining, testing, and inspecting the plant, as well as processes that ensure
3 facility safety through its operational lifetime; and (3) risk-informed strategies that manage the
4 risks of accidents, including the strategies of accident prevention and mitigation.
5

6 During the operational period, licensees can draw upon risk insights gained from the analyses
7 used to demonstrate compliance with the performance objectives for operations including
8 protection of the general population, protection of inadvertent intruders, and protection of
9 individuals during operations (i.e., 10 CFR 61.41 through 10 CFR 61.43) to demonstrate that
10 defense-in-depth protections are included. The defense-in-depth analyses for an operating land
11 disposal facility are expected to be similar to demonstrations of defense-in-depth for other
12 operating facilities that use radioactive materials (e.g., nuclear reactors). For instance, the land
13 disposal facility would use procedures and engineering controls as part of a radiation control
14 program, required by 10 CFR 20.1101, to minimize occupational doses and doses to members
15 of the public. In this example, the licensee would need to identify the specific procedures and
16 controls that are relied upon for safety should plausible scenarios that challenge safety functions
17 occur, describe the safety functions associated with the procedures and controls and when
18 those safety functions are expected to be necessary, as well as describe the uncertainty in the
19 safety functions to perform adequately.
20

21 Licensees can use the results of analyses that are similar to those used at other nuclear
22 facilities (e.g., an integrated safety analysis as described in NUREG-1513 (NRC, 2001) for
23 licensing of special nuclear material) to demonstrate that no single layer of defense will be
24 exclusively relied upon for safety at an operating land disposal facility. The amount of detail
25 needed for a land disposal facility may be markedly different than for other facilities depending
26 upon the hazards present and the risks involved in the use of the radioactive material at the
27 disposal facility or the handling of waste for disposal.
28

29 Licensees should examine whether the layers of defense, their associated safety functions, and
30 uncertainty ensure safety during operations by limiting the likelihood or consequences during
31 reasonably foreseeable and less likely, but plausible scenarios. For facilities or activities with
32 more significant hazards (e.g., emplacement of high activity waste), which could result in
33 significant potential exposures to workers or the public during operations, additional redundancy
34 and a stronger basis for independence among the layers may be necessary. Reviewers should
35 consider potential exposures from plausible scenarios during operations of a land disposal
36 facility as significant for the purposes of defense-in-depth when they are expected to exceed the
37 occupational dose limits or the dose limits for members of the public specified in 10 CFR
38 Part 20, Subparts C and D, respectively. For plausible scenarios with significant exposures,
39 licensees should consider additional layers of defense, further redundancy, improved
40 independence, or reduced uncertainty in the safety function of the layers to ensure that the
41 likelihood of significant exposures is reduced so that the scenario becomes implausible or that
42 the consequences are sufficiently reduced.

43 **8.3.3.2 Post-Closure Period**

44

45 Following closure of the land disposal facility, defense-in-depth protections shift from a
46 collection of active and passive barriers and controls that are used during operations to reliance
47 on controls and passive barriers. Defense-in-depth protections for the post-closure period may
48 include, but are not limited to, engineered features (e.g., closure caps, wasteforms, and

1 containers) and natural characteristics (e.g., hydrogeology) of the disposal site that are intended
2 to contain and isolate the waste, as well as controls such as institutional controls, which are
3 designed to limit access to the disposal site for a limited period of time, and waste acceptance
4 requirements, which are designed to limit the radionuclide inventory in the disposal site.

5
6 As a result of increasing uncertainty in the behavior of the layers of defense, particularly
7 barriers, and the disposal site environment, the associated uncertainty in the margin of safety
8 provided by the layers of defense is also expected to increase. In addition to the barriers
9 themselves, licensees may also need to consider additional controls to ensure that the barriers
10 relied upon for safety will perform adequately. These controls may include quality assurance
11 controls during the design, construction, operation, and maintenance of engineered barriers
12 (e.g., engineered closure caps, wasteforms, or containers) or, more importantly, given the long
13 timeframes involved, additional inventory controls to limit the amount of waste disposed at the
14 disposal site. Development of waste acceptance criteria is described further in Section 9.0.

15
16 For the post-closure period, licensees can draw upon risk insights gained from the results of the
17 other 10 CFR 61.13 post-closure analyses (i.e., performance assessment, intruder assessment,
18 and stability analyses) rather than developing specific analyses for demonstrating that defense-
19 in-depth protections are included. Those other 10 CFR 61.13 analyses are expected to focus
20 on protections that can maintain safety, in the context of the post-closure performance
21 objectives, for the disposed waste over the various regulatory time periods that are pertinent.
22 The post-closure period is subdivided into three timeframes: the compliance period, the
23 protective assurance period, and the performance period. Depending upon the waste received,
24 the performance period may not apply to the land disposal facility and defense-in-depth
25 analyses may not be needed for the longer-term period (i.e., analyses that extend beyond
26 10,000 years). Because 10 CFR Part 61 does not envision ongoing active maintenance and
27 monitoring at the disposal site, the layers of defense for these three time periods are expected
28 to be primarily barriers and inventory limits after 100 years following closure, when the
29 institutional controls are assumed to no longer be effective.

30
31 Licensees can use results from the uncertainty analyses performed for the other 10 CFR 61.13
32 analyses to demonstrate that adequate defense-in-depth protections are included. For
33 instance, Section 7.4 describes how to conduct barrier analyses for demonstrating compliance
34 during the performance period. Barrier analyses are common uncertainty analyses performed
35 as part of a performance assessment, and though the guidance in Section 7.4 is focused on the
36 performance period, it is generally applicable to conducting barrier analyses for any of the post-
37 closure time periods. By examining the consequences of early degradation or failure of one or
38 more of the layers of defense, licensees can demonstrate that safety can be maintained or
39 determine that additional layers of defense, further redundancy, improved independence, or
40 reduced uncertainty in the safety function of a layer may be needed.

41
42 To demonstrate that the layers of defense are adequate, licensees should examine not only the
43 reasonably foreseeable scenarios considered for demonstrating that the performance objectives
44 would be met, but also less likely, but plausible scenarios (e.g., accidents, disruptive events,
45 abnormal occurrences). If the performance objectives are met, significant consequences are
46 generally not expected for reasonably foreseeable scenarios. However, significant
47 consequences may be possible for less likely, but plausible scenarios. The following sections
48 provide guidance on when additional layers of defense, further redundancy, improved

1 independence, or reduced uncertainty in the safety function of a layer may be needed to
2 demonstrate that adequate defense-in-depth protections are included for each of the three post-
3 closure time periods.

4 8.3.3.2.1 *Compliance Period*

5

6 During the compliance period, uncertainty in the behavior of the layers of defense and the
7 evolution of the disposal site environment at a well-sited disposal facility is expected to be more
8 manageable than for longer time periods. In terms of the disposal site and design, licensees
9 should demonstrate that the margin of safety determined by the layers of defense provides
10 confidence that the limits specified in 10 CFR 61.41(a) and 10 CFR 61.42(a) are not expected to
11 be exceeded for the central scenario. To demonstrate that an adequate margin of safety is
12 available, licensees could compare probabilistic dose curves derived from the analyses used to
13 demonstrate that the performance objectives are met below the designated limit. At a minimum,
14 unless otherwise authorized, licensees must demonstrate that the specified limit is not
15 exceeded for the mean doses during the compliance period to demonstrate that the
16 performance objectives are met. If the peak of the mean dose curve exceeds the specified limit,
17 then additional layers of defense or added redundancy are necessary for engineering design of
18 the facility or the disposal site to be appropriate for disposal. Guidance on demonstrating that
19 the performance objectives are met is described in Section 3.0 for protection of the general
20 population and Section 4.0 for protection of inadvertent intruders. Guidance on demonstrating
21 the long-term stability of the disposal site is discussed in Section 5.0.

22
23 Once licensees demonstrate that the performance objectives are met, they should demonstrate
24 that an adequate margin of safety is provided by the layers of defense such that significant
25 exposures, which would require future intervention to mitigate, would not be expected to occur.
26 To do this, licensees should demonstrate that the 95th percentile of annual doses from
27 probabilistic analyses of the central scenario at each discrete time during the compliance period
28 is less than the dose limits for members of the public (i.e., 1 mSv [100 mrem]), as described in
29 Section 3.2.4.3 of NUREG-1573 (NRC, 2000a), and less than 20 mSv (2 rem) for protection of
30 inadvertent intruders, an exposure level for human intruders above which alternative options for
31 waste disposal are to be considered (IAEA, 2011).

32
33 Additionally, if the peak annual dose from any single or subset of realizations of the central or
34 alternative scenarios exceeds 50 mSv (5 rem) for either protection of the general population or
35 inadvertent intruders, licensees should examine those realizations (or alternative scenarios) to
36 determine whether additional layers of defense, independence, or redundancy would be
37 beneficial. The 50 mSv (5 rem) guidance threshold provides confidence that any plausible
38 projected scenario would not be expected to exceed a level that would almost always justify
39 intervention in an emergency situation. The ICRP advises that intervention would almost
40 always be justified for existing exposures that would exceed 100 mSv (10 rem) (ICRP, 2007). In
41 this case, additional layers of defense, independence or redundancy should ensure that doses
42 for any plausible scenario are maintained well below levels where future intervention to mitigate
43 significant exposures would be necessary or that the likelihood of the realization would be
44 reduced by the additional layers of defense to render it implausible.

45
46 If a licensee performs deterministic rather than probabilistic analyses, the licensee should
47 demonstrate that all annual doses from reasonably foreseeable or less likely, but plausible

1 scenarios are less than 1 mSv (100 mrem) for protection of the public and less than 20 mSv
2 (2 rem) for protection of inadvertent intruders, in order to ensure doses would be maintained
3 well below levels where future intervention to mitigate significant exposures would be
4 necessary.

5
6 Disposal facilities that could result in potential doses from reasonably foreseeable or less likely
7 but plausible scenarios that exceed those mentioned in the previous paragraphs during the
8 compliance period are considered higher-risk disposal facilities. Licensees should employ
9 additional layers of protection or ensure that sufficient independence and redundancy will be
10 provided to ensure that common-cause failures are minimized and adequate redundancy in the
11 safety function is provided so that a significant exposure is highly unlikely to occur.

12 8.3.3.2.2 *Protective Assurance Period*

13
14 During the protective assurance period, uncertainty in the behavior of the layers of defense and
15 the evolution of the disposal site environment is expected to increase, due to lack of knowledge
16 about the key properties of the layers of defense and the disposal site environment, as well as
17 FEPs and human activities that may occur in the future at or near the disposal site. In terms of
18 the disposal site and design, licensees should demonstrate that the margin of safety determined
19 by the layers of defense provides confidence that the exposures will be below a reasonably
20 achievable level, as required in 10 CFR 61.41(b) and 10 CFR 61.42(b), for the central scenario.
21 The performance objectives for the protective assurance period require the minimization of
22 exposures, with a goal of limiting the annual dose below 5 mSv (500 mrem) or a level that is
23 reasonably achievable based on technological and economic considerations. Therefore, at a
24 minimum, licensees must demonstrate that the specified minimization goal for the disposal site
25 is met. If the minimization goal is not met, licensees would need to add additional barriers or
26 impose additional controls to demonstrate that the minimization goal will be met. Guidance on
27 developing minimization targets and demonstrating that minimization is met is provided in
28 Section 6.0.

29
30 Once licensees demonstrate that the performance objectives are met, licensees should
31 demonstrate that an adequate margin of safety is provided by the layers of defense for the
32 protective assurance period such that significant consequences are minimized for plausible
33 scenarios. Licensees should be able to draw risk insights from the results of the performance
34 assessment (see Section 3.0), intruder assessment (see Section 4.0), and site stability analyses
35 (see Section 5.0) to estimate safety functions and their associated uncertainty during the
36 protective assurance period.

37
38 To demonstrate that an adequate margin of safety is provided for the protective assurance
39 period, licensees should demonstrate that the layers of defense maintain the peak annual dose
40 from any single or subset of realizations (or from a less likely, but plausible alternative scenario
41 for a deterministic analyses) below 50 mSv (5 rem) for either protection of the general
42 population or inadvertent intruders. The 50 mSv (5 rem) guidance threshold provides
43 confidence that any plausible projected scenario would not be expected to exceed a level that
44 would almost always justify intervention in an emergency situation. The ICRP advises that
45 intervention would almost always be justified for existing exposures that would exceed 100 mSv
46 (10 rem) (ICRP, 2007). Disposal facilities that could result in potential doses from reasonably
47 foreseeable or less likely, but plausible scenarios that exceed 50 mSv (5 rem) during the
48 protective assurance period are considered higher-risk disposal facilities.

1
2 At higher-risk facilities, licensees should employ additional layers of protection or ensure that
3 sufficient independence and redundancy will be provided to ensure that common-cause failures
4 are minimized and adequate redundancy in the safety function is provided so that a significant
5 exposure is highly unlikely to occur. In deciding whether additional layers of defense would be
6 needed, licensees may consider technological or economic limitations to employing additional
7 barriers. However, the additional cost of limiting inventory is typically not expected to be overly
8 burdensome from either a technical or economic consideration and is expected to provide the
9 greatest certainty that the performance objectives can be met. Therefore, licensees and
10 reviewers should strongly consider additional inventory limits as added controls or alternative
11 siting to ensure the performance of the existing barriers when other additional layers of defense
12 may not be practical for technological or economic reasons.

13 8.3.3.2.3 *Performance Period*

14
15 During the performance period, uncertainty in the behavior of the layers of defense and the
16 evolution of the disposal site environment is expected to be significantly larger than other
17 analysis time periods. The increased uncertainty is due to lack of knowledge about the key
18 properties of the layers of defense and the disposal site environment as well as FEPs and
19 human activities that may occur in the future at or near the disposal site. As a result of
20 increasing uncertainty in FEPs that could be expected to occur, the associated uncertainty in
21 the margin of safety provided by the layers of defense is also expected to increase.
22

23 In terms of the disposal site and design, licensees should demonstrate that the the layers of
24 defense provide confidence that releases and exposures will be minimized to the extent
25 reasonably achievable, as specified in 10 CFR 61.41(c) and 10 CFR 61.42(c), respectively.
26 Guidance on developing demonstrating that minimization is met for the performance period is
27 provided in Section 7.0.
28

29 Once licensees demonstrate that the performance objectives are met, licensees should
30 demonstrate that an adequate margin of safety is provided by the layers of defense for the
31 performance period such that significant consequences are minimized for plausible scenarios.
32 To demonstrate that an adequate margin of safety is maintained during the performance period,
33 licensees should demonstrate that the layers of defense maintain releases from the disposal
34 site that result in exposures to the general population or exposures to an inadvertent intruder at
35 or below 50 mSv (5 rem). The 50 mSv (5 rem) guidance threshold provides confidence that any
36 plausible projected scenario would not be expected to exceed a level that would almost always
37 justify intervention in an emergency situation. The ICRP advises that intervention would almost
38 always be justified for existing exposures that would exceed 100 mSv (10 rem) (ICRP, 2007).
39 Disposal facilities that could result in potential doses that exceed 50 mSv (5 rem) for plausible
40 scenarios during the performance period are considered higher-risk disposal facilities.
41 Licensees may also be able to develop alternative measures of safety margin. For instance,
42 licensees could compare concentrations in media to concentrations that would require
43 intervention today should a less likely, but plausible scenario occur.
44

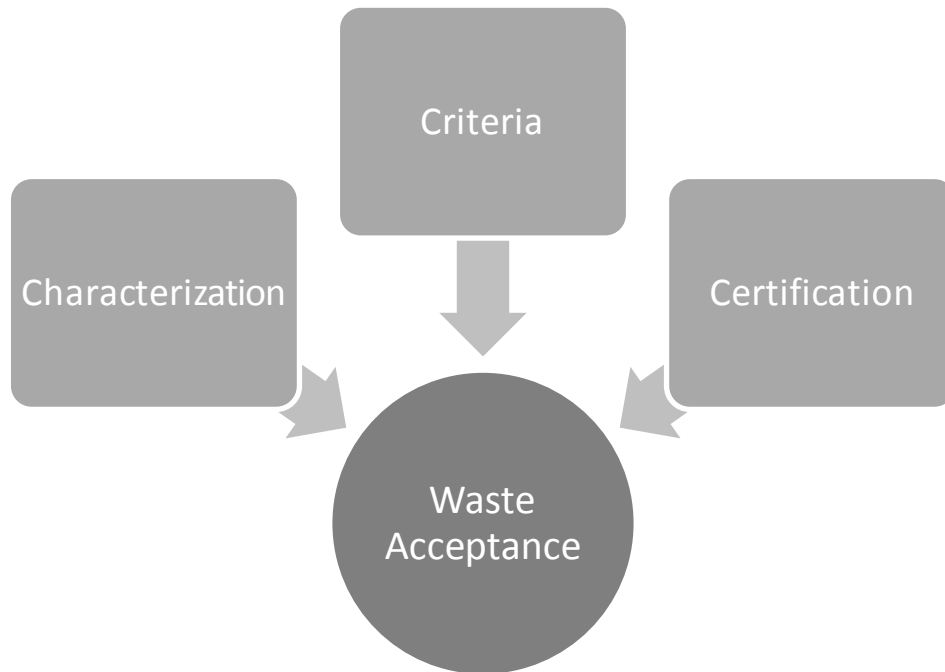
45 Disposal facilities that could result in potential doses from reasonably foreseeable or less likely
46 but plausible scenarios that exceed those mentioned in the previous paragraphs during the
47 compliance period are considered higher-risk disposal facilities. Licensees should employ

1 additional layers of protection or ensure that sufficient independence and redundancy will be
2 provided for the disposal site to ensure that common-cause failures are minimized and
3 adequate redundancy in the safety function is provided so that a significant exposure is highly
4 unlikely to occur.
5

6 In deciding whether additional layers of defense would be needed, licensees may consider
7 technological or economic limitations to employing additional barriers. However, the additional
8 cost of limiting inventory is typically not expected to be overly burdensome from either a
9 technical or economic consideration and is expected to provide the greatest certainty that the
10 performance objectives can be met. Therefore, licensees and reviewers should strongly
11 consider additional inventory limits as added controls or alternative siting to ensure the
12 performance of the existing barriers when other additional layers of defense may not be
13 practical for technological or economic reasons.
14
15
16
17
18

1 **9.0 WASTE ACCEPTANCE**

2
3 Section 61.23 of 10 CFR Part 61 specifies standards that must be met to receive a license to
4 operate a land disposal facility for LLW. The standards require licensees to demonstrate that
5 the waste acceptance criteria and other components of the licensee’s proposal are adequate to
6 protect public health and safety and provide reasonable assurance that the performance
7 objectives specified in Subpart C will be met. The regulations at 10 CFR 61.58 specify the
8 requirements for waste acceptance. The regulations require licensees to identify (i) criteria for
9 the acceptance of waste for disposal, (ii) acceptable methods for characterizing the waste, and
10 (iii) a program to certify that waste meets the acceptance criteria prior to receipt at a land
11 disposal facility for radioactive waste. Figure 9-1 illustrates the main components of waste
12 acceptance under 10 CFR Part 61. The regulations also require licensees to review the content
13 and implementation of the waste acceptance criteria, characterization methods, and certification
14 program at least annually.
15
16



17
18
19 **Figure 9-1 Waste Acceptance Components**

20
21 This section describes the information that a licensee should provide and a reviewer should
22 evaluate with respect to the waste acceptance requirements. First, the waste acceptance
23 criteria identify the following for waste generators: (1) the allowable limits on radionuclides,
24 (2) acceptable wastefoms and container specifications, and (3) restrictions or prohibitions in
25 order for waste to be accepted for disposal as LLW. Section 9.1 describes information that
26 licensees should provide to demonstrate that the waste acceptance criteria will be adequate.
27 Second, in order to demonstrate that the waste meets the acceptance criteria, waste must be
28 adequately characterized. Section 9.2 provides guidance to licensees on defining acceptable

1 methods for waste characterization. Finally, waste must
2 be certified to ensure that waste meets the acceptance
3 criteria and is, therefore, suitable for disposal in a land
4 disposal facility. Section 9.3 describes information that
5 licensees should include in a certification program to
6 ensure that waste received at the disposal facility is
7 acceptable for disposal.

8 **9.1 Waste Acceptance Criteria**

9
10 Section 61.52 of 10 CFR Part 61 requires that all waste
11 disposed in the disposal site must meet approved waste
12 acceptance criteria. Section 61.58 of 10 CFR Part 61
13 requires licensees to submit proposed waste
14 acceptance criteria for approval. Once the disposal site
15 regulator approves the waste acceptance criteria,
16 licensees wishing to make modifications to the criteria
17 must request an amendment. This section provides
18 guidance on developing or modifying waste acceptance
19 criteria and discusses information that licensees should
20 include in order to allow a regulator to evaluate whether
21 the proposed waste acceptance criteria provide
22 reasonable assurance that the performance objectives
23 will be met.

24
25 Section 61.58 of 10 CFR Part 61 specifies the
26 requirements for waste acceptance at a disposal facility
27 for LLW. Waste acceptance criteria are intended to
28 provide reasonable assurance that the performance objectives of 10 CFR Part 61 will be met.
29 The regulations require licensees to identify the criteria for the acceptance of waste for disposal
30 (i.e., waste acceptance criteria). Specifically, the regulations require that the waste acceptance
31 criteria specify, at a minimum, allowable activities and concentrations of specific radionuclides,
32 acceptable wasteform characteristics and container specifications, and restrictions or
33 prohibitions on waste, materials, or containers. Figure 9-2 depicts the minimum components of
34 the waste acceptance criteria.

35
36 Licensees may need to specify other criteria beyond those required by 10 CFR Part 61 to satisfy
37 other regulatory requirements. For instance, land disposal facilities may also be required by
38 other Federal or State regulations to limit certain non-radiological materials because of their
39 impact on public health and safety and the environment. This guidance document focuses only
40 on the waste acceptance criteria required by 10 CFR Part 61.

41 **9.1.1 Allowable Activities and Concentrations**

42
43 The waste acceptance requirements of 10 CFR Part 61 allow licensees the option to develop
44 allowable limits from either the technical analyses required in 10 CFR 61.13 for any land
45 disposal facility or the waste classification limits in 10 CFR 61.55 for a near-surface disposal
46 facility. For instance, licensees disposing of waste that is similar to the waste streams
47 considered in the development of the waste classification limits may wish to rely on those limits.



Figure 9-2 Components of 10 CFR Part 61 Waste Acceptance Criteria

1 Whereas, licensees disposing of waste streams beyond those considered for the waste
2 classification requirements may wish to determine limits from the results of their technical
3 analyses. Likewise, licensees with facility designs, operational practices, or site characteristics
4 that differ significantly from those considered to develop the waste classification limits, may also
5 wish to develop site-specific waste acceptance criteria. The unique characteristics of the waste
6 in concert with the disposal site and design are the primary determinants of risk from near-
7 surface disposal. Thus, not all radioactive waste streams may be suitable for near-surface
8 disposal.

9
10 This section of the guidance document describes the information that a licensee should provide
11 and that a reviewer should evaluate with respect to the development of allowable activities and
12 concentrations for radionuclides. Reviewers may want to consult Standard Review Plan 6.1.1 of
13 NUREG-1200 (NRC, 1994) to ensure that the allowable limits specified by the licensee's waste
14 acceptance criteria are reasonable, given the types and quantities of radionuclides projected for
15 disposal.

16 **9.1.1.1 Allowable Limits Derived from Technical Analyses**

17
18 Radioactivity disposed in a land disposal facility may need to be limited to ensure (i) protection
19 of the general public from releases during operations and after operations have ceased, (ii)
20 protection of individuals who may inadvertently intrude into the disposal site after active
21 institutional controls are removed, (iii) protection of individuals during operations, and (iv)
22 stability of the disposal site after closure. Limits on radioactivity disposed in a land disposal
23 facility can also provide defense-in-depth. The limits may vary widely from site-to-site
24 depending on the waste streams proposed for disposal, facility design, and site characteristics.

25
26 Licensees who elect to develop limits on radionuclide activities or concentrations from the
27 results of the analyses required in 10 CFR 61.13 should document how the proposed limits are
28 developed from the analyses performed to satisfy the requirements of 10 CFR 61.13. The
29 proposed limits should focus on radionuclides that may affect meeting the performance
30 objectives. These limits may be unique for specific waste streams or total limits for the disposal
31 site. Proposed limits for specific waste streams may be more appropriate when unique factors
32 may affect meeting one or more of the 10 CFR Part 61 performance objectives such as the
33 anticipated release from a particular wasteform, the concentrations of radionuclides in the
34 waste, the potential for criticality due to the presence of special nuclear material in the waste,
35 the radiation fields emanating from the waste, or the heat generated by the decaying waste.

36
37 Licensees should develop allowable limits, either total activity or concentration, from the
38 resulting peak doses from a unit activity of each radionuclide for the performance objective
39 which is the most limiting for each radionuclide. When evaluating each performance objective,
40 the licensee should use the scenario(s) used to demonstrate that the performance objectives
41 are met to establish the limits. Selection of the scenario(s) for demonstrating compliance with
42 the performance objectives is described in Sections 2.0, 3.0, and 4.0 of this document. To
43 develop limits, licensees should compare the peak dose for each radionuclide with the limits
44 specified by the performance objective.

1 Licensees may calculate a limit for each radionuclide using:
2

$$3 \quad \text{Limit}_{i,s} = \frac{\text{Dose Limit}_s \times \text{Activity}(0)_i}{\text{Peak Dose}_{i,s}} \quad (9.1)$$

4 where

5 $\text{Limit}_{i,s}$ is the total activity [Bq] or activity concentration [Bq/m³ or Bq/g] limit of
6 radionuclide i in waste for scenario s ;

7

8 Dose Limit_s is the dose limit [mSv/yr] for scenario s ;

9

10 $\text{Activity}(0)_i$ is the initial total activity [Bq] or activity concentration [Bq/m³ or Bq/g] of
11 radionuclide i in the waste; and

12

13 $\text{Peak Dose}_{i,s}$ is the annual peak dose [mSv/yr] resulting from the $\text{Activity}(0)_i$ of radionuclide i
14 for scenario s .

15

16 Licensees should clearly identify the technical basis for each allowable limit specified in the
17 waste acceptance criteria. The basis for each proposed limit should include the performance
18 objective(s) that the limits are designed to support. For instance, proposed limits for some
19 radionuclides may be more relevant to protection of facility workers during operations than to
20 protection of the general public from releases. The basis should also emphasize why each
21 proposed limit is sufficient to demonstrate that the performance objectives will be met.

22 Licensees will also need to demonstrate that the individual limits, when taken together, will
23 ensure that the performance objectives continue to be met.

24

25 Licensees should describe in the technical basis supporting the allowable limits how they
26 account for variability and uncertainty in anticipated inventories when developing the allowable
27 limits. One method to mitigate uncertainty is to manage it through controls or restrictions. A key
28 control to account for variability and uncertainty is imposing limits on the radionuclide inventory
29 of disposed waste. The inventory of radionuclides in the waste disposed can be readily
30 controlled, whereas uncertainty associated with the natural system or engineered barriers, for
31 example, may be difficult to define or, if understood, difficult to reduce. The following general
32 guidelines are useful for the development of allowable limits under 10 CFR 61.58:

33

34 • Allowable limits should be established conservatively so as to reduce the need for future
35 mitigation.

36 • The analysis used to develop allowable limits should be as complete as practicable and
37 include uncertainties.

38

39 The allowable limits will be affected by the complexity of the disposal site and its environment,
40 the conservatism in the analyses, and the amount of information available to support the
41 assessment. Figure 9-3 provides the relative change in the safety factor with changes in the
42 relative value of these variables. For example, when the amount of information available to
43 support the analyses is relatively large, licensees may apply a small margin of safety to the
44 results of the analyses to establish the limits. On the other hand, if the disposal site
45 environment is complex, licensees may need to apply a large margin of safety in order to

1 provide reasonable assurance the performance objectives will be met. In other words, the
 2 uncertainty in the risk will be a primary driver of the values for the limits. There is no absolute
 3 value (e.g., an inventory that corresponds to 10 percent of the 0.25 mSv/yr or 25 mrem/yr dose
 4 limit) that is appropriate to use to establish limits for all sites. Allowable limits can be viewed as
 5 one of several safety factors or defense-in-depth protections used to mitigate uncertainty in
 6 other (i.e., non-inventory) areas of the technical analyses.

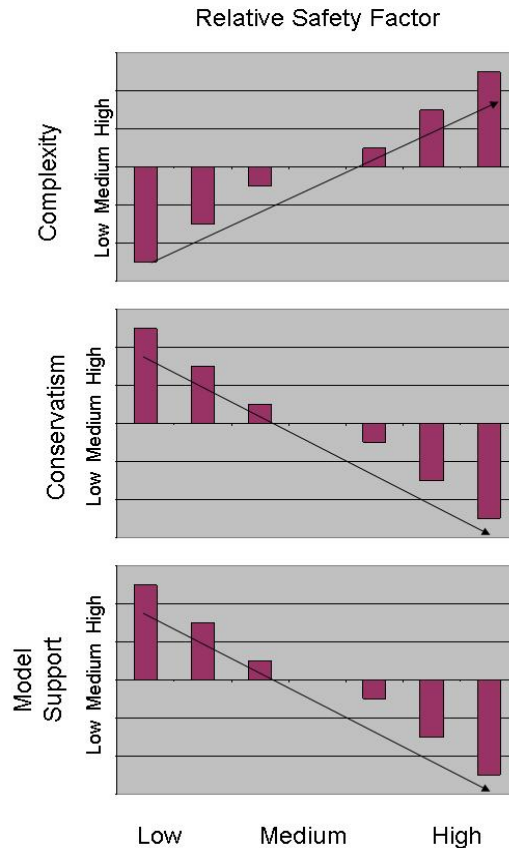


Figure 9-3 Influence of Key Variables on the Required Relative Safety Factors

7
 8 Reviewers should coordinate reviews of the allowable limits with the reviews of the technical
 9 analyses required to meet 10 CFR 61.13 (see Sections 3.0, 4.3, and 8.0 of this document).
 10 Reviewers should verify that the licensee's proposed limits on activities and concentrations are
 11 adequate, considering the source term inventory used in the performance and intruder
 12 assessments as well as assessments of expected and accidental occupational exposures
 13 during handling, storage, and disposal of waste.

14
 15 In general, the proposed limits should be consistent with the source term evaluated in the
 16 technical analyses. However, licensees may use a variety of approaches to develop allowable
 17 limits. For example, a licensee may derive a limit from the results of one or more of the

1 analyses for a source term with a unit concentration (e.g., 1.0 nCi/g) that is then scaled to the
2 limit specified by the relevant performance objective. In this example, the proposed limits would
3 not be expected to be consistent with the source term employed in the analyses. Rather, the
4 limits should be consistent with the outcome of the analyses that meets the performance
5 objective. Regardless of the approach, the reviewer should evaluate whether the approach is
6 appropriate. Assuming a source term with unit concentrations of disposed waste may not be
7 appropriate in circumstances where the radiological exposures are non-linearly correlated to
8 source term concentrations.

9
10 Reviewers should also assess the spatial extent and distribution of the radionuclide inventory
11 evaluated in the analyses to determine whether the allowable proposed limits are appropriate
12 (e.g., when considering the disposal facility's operating procedures for emplacement). In some
13 cases, depending on the scenarios evaluated in the technical analyses to demonstrate the
14 performance objectives are met, the spatial extent or distribution of radionuclide inventory in the
15 disposal site may also need to be controlled as an allowable limit. For example, a licensee
16 develops a total average activity concentration limit for a particular radionuclide from the intruder
17 assessment based on an expected volume to which the intruder may be inadvertently exposed.
18 Reviewers should confirm that the facility's operating procedures would reasonably ensure that
19 the proposed limit would not be expected to be exceeded for any volume of the disposal unit
20 equivalent to the intrusion volume assumed by the licensee in the assessment.

21
22 Reviewers should evaluate how stability is considered when establishing the allowable limits.
23 First, stable wasteforms or containers may allow the disposal of waste with higher radioactivity
24 than unstable waste. Therefore, reviewers should evaluate the estimated performance of the
25 wasteforms, containers, or other design features that provide stability. Reviewers should
26 coordinate this review with the review of acceptable wasteforms and containers, which is
27 described Section 9.1.2 of this document. Reviewers should confirm that licensees are
28 establishing waste acceptance criteria for wasteforms, containers, or design features that
29 provide assurance the expected performance can be achieved. Second, there may be cases
30 where the radionuclide inventory could significantly affect the stability of the disposal site after
31 closure. For example, reviewers may need to evaluate whether radiation fields or thermal
32 output from radioactive decay for certain higher activity waste streams would significantly
33 compromise structural stability of the waste containers or degradation of the wasteforms and
34 lead to stability issues for the disposal unit. Reviewers should coordinate their review of the
35 development of allowable limits from the technical analyses with their review of acceptable
36 wasteform characteristics and container specifications (see Section 9.1.2).

37
38 In general, reviewers should focus their review of allowable limits on those radionuclides
39 expected to contribute most significantly to risk to the public, workers, and the environment.
40 Typically, radionuclides with relatively high solubility, low sorption, high dose conversion factors,
41 and/or significant in-growth are of particular significance. However, the importance of
42 radionuclides may vary based upon the specific performance objective under consideration. For
43 instance, non-mobile radionuclides may be more significant for protection of inadvertent
44 intruders.

45
46 Reviewers should also evaluate whether the technical basis provided for each proposed limit
47 will provide assurance that all the performance objectives will be met. For example, if an
48 allowable limit is set for a particular radionuclide based on the results of the performance
49 assessment, reviewers should confirm that the limit would not preclude licensees from

1 demonstrating that the other performance objectives (e.g., protection of inadvertent intruders via
2 the intruder assessment) are met. This review should also ensure that the allowable limits are
3 comprehensive and that all necessary limits are included. Reviewers may elect to conduct
4 independent analyses to inform the review.

5 **9.1.1.2 Allowable Limits Derived from Waste Classification**

6
7 Licensees who elect to develop allowable limits for radionuclides from the 10 CFR Part 61
8 waste classification requirements may simply report the concentration limits reported in 10 CFR
9 61.55. The limits specified in 10 CFR 61.55 shall be applied on a per package basis.

10 Licensees may also need to develop alternative limits for radionuclides not listed in the tables,
11 particularly for waste that is significantly different than what was considered in the analyses
12 used to develop the tables (see NRC, 1981a). Tables 4.1 and 4.2 of NUREG-0945, Volume 1
13 (NRC, 1982b) list the waste streams and radionuclides considered in the analyses to develop
14 the tables. Guidance on developing limits on radionuclides not listed in the waste classification
15 tables is also provided in this section.

16
17 The concentration limits reported in 10 CFR 61.55, together with the requirements for waste
18 characteristics, 10 CFR 61.56, and segregation, 10 CFR 61.52(a)(1) and (2), provide
19 reasonable assurance that an intruder would be protected should they inadvertently be exposed
20 to the waste that has been disposed in a facility. Classification involves consideration of both
21 (1) long-lived radionuclides, whose potential hazard will persist long after precautions such as
22 institutional controls, improved wastefrom, and deeper disposal have ceased to be effective;
23 and (2) shorter-lived radionuclides, for which such precautions can be effective.

24
25 Classification is also used to determine which waste characteristics requirements in
26 10 CFR 61.56 are necessary. Further, classification is used to determine the waste segregation
27 requirements in 10 CFR 61.52 that the disposal facility must meet during operations. Waste
28 segregation provides assurance that waste is disposed of in a manner that limits potential
29 exposures, including those to an inadvertent intruder, based on the hazard and stability of the
30 waste. Figure 9-4 illustrates the waste classification and segregation requirements for LLW.
31 Thus, licensees relying on the waste classification system to develop allowable limits must also
32 ensure that criteria for both acceptable wastefrom characteristics and facility operating practices
33 are consistent with the related requirements for waste characteristics and segregation. Further
34 guidance on developing criteria for acceptable wastefrom characteristics is provided in Section
35 9.1.2 of this document.

36
37 Licensees can demonstrate compliance with the classification requirements for selected
38 radionuclides by comparing radionuclide concentrations in LLW to the values listed in the tables
39 of long- and short-lived radionuclides in 10 CFR 61.55. The radionuclide concentrations listed
40 in the classification tables were developed, in part, from two considerations: direct contact with
41 the disposed waste (i.e., intrusion) and potential consumption or use of contaminated
42 groundwater (i.e., migration).

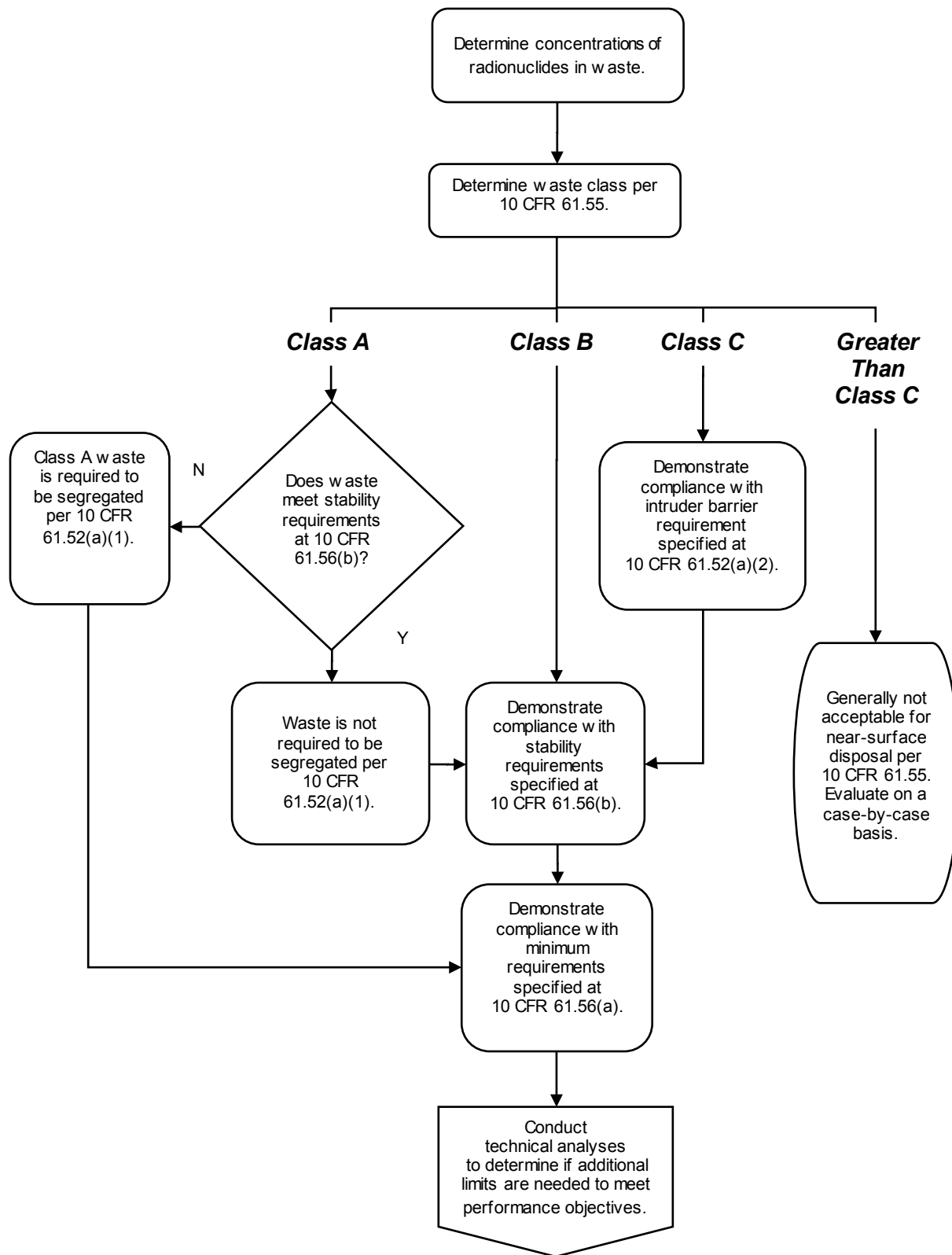


Figure 9-4 Waste Classification and Segregation for Waste Classes

1 The approach, established in NUREG-0782 (NRC, 1981a), first considered protection of the
2 individual inadvertent intruder. The approach then identified a limited set of radionuclides that
3 are significant from the standpoint of migration. Radionuclides significant from the standpoint of
4 migration are generally more important for protection of the general population; therefore, the
5 NRC staff expected these radionuclides to be evaluated as part of the demonstration that the
6 performance objective for protection of the general population (i.e., 10 CFR 61.41) is met.
7 Therefore, the waste classification requirements were primarily derived from the analysis for
8 protection of the inadvertent intruder.

9
10 For near-surface disposal, 10 CFR 61.55 specifies the three classes of waste, A, B, and C, that
11 resulted from the analysis. Upper concentration limits are also defined for Class C waste.
12 Wastes containing radionuclide concentrations higher than the upper limits would be generally
13 unacceptable for near-surface disposal. However, there may be instances where these wastes
14 would be acceptable for near-surface disposal with special processing or design. These
15 instances would be evaluated on a case-by-case basis.

16
17 Wastes for which there are no stability requirements, but which must be disposed of in a
18 segregated manner from other wastes, are termed "Class A." These wastes are defined in
19 terms of maximum allowable concentrations of certain isotopes and certain minimum
20 requirements on wasteform that are necessary for safe handling. The minimum requirements
21 are specified in 10 CFR 61.56(a). Waste designated as Class A must be segregated from other
22 waste as required in 10 CFR 61.52(a)(1), unless a licensee can demonstrate that the waste also
23 meets the stability requirements specified in 10 CFR 61.56(b). The technical analyses required
24 in 10 CFR 61.13 could demonstrate based on site-specific conditions that additional disposal
25 practices or waste characteristics—such as those required for Class B or C wastes—would be
26 necessary to demonstrate that the performance objectives are met.

27
28 Wastes that need to be placed in a stable form and disposed of in a segregated manner from
29 unstable wasteforms are termed "Class B." These stable wastes are also defined in terms of
30 allowable concentrations of isotopes and requirements for a stable wasteform as well as
31 minimum handling requirements. The minimum requirements are specified at 10 CFR 61.56(a),
32 and the stability requirements are specified at 10 CFR 61.56(b). Further, the technical analyses
33 could demonstrate that additional disposal practices or waste characteristics, such as those
34 required for Class C waste, would be necessary, based on site-specific conditions, to
35 demonstrate that the performance objectives are met.

36
37 Wastes that need to be placed into a stable form, disposed of in a segregated manner from
38 unstable wasteforms, and disposed of so that a barrier is provided against potential inadvertent
39 intrusion after institutional controls are no longer assumed to be effective are termed "Class C."
40 These intruder wastes are also defined in terms of allowable concentrations of isotopes and
41 requirements for disposal by deeper burial or some other intruder barrier, as well as minimum
42 stability requirements. The minimum requirements for waste characteristics are specified at
43 10 CFR 61.56(a), and the stability requirements are specified at 10 CFR 61.56(b).
44 Requirements for near-surface disposal by deeper burial or some other barrier are specified at
45 10 CFR 61.52(a)(2). The technical analyses could demonstrate that additional disposal
46 requirements, such as the longevity of the intruder barriers, or limits on the radionuclide
47 inventory, are necessary to provide reasonable assurance that the performance objectives
48 would be met.

1 Because the classification limits were developed primarily from an analysis that examined
2 inadvertent intrusion, the limits are not intended to provide reasonable assurance that all the
3 performance objectives of 10 CFR Part 61 will be met. Therefore, licensees using the waste
4 classification requirements may need to develop additional limits based on the results of the
5 technical analyses used to demonstrate that the remaining performance objectives would be
6 met. For example, radionuclides that are prone to migration may require additional limits to
7 ensure that the 10 CFR 61.41 performance objective will be met.

8
9 As specified in 10 CFR 61.55(a)(6), waste that does not contain any radionuclides listed in
10 either Table 1 or 2 is considered Class A. As such, this waste is subject to the same
11 requirements as Class A waste that does contain radionuclides listed in either Table 1 or 2.
12 However, the technical analyses could demonstrate that additional disposal practices, such as
13 those required for Class B or C wastes, are necessary to provide reasonable assurance that
14 public health and safety will be protected. Therefore, licensees may also need to specify limits
15 for those radionuclides that are not specifically identified in the waste classification requirements
16 in 10 CFR 61.55 if the radionuclides significantly affect the demonstration that the performance
17 objectives would be met. In these cases, licensees should refer to Section 9.1.1.1 for guidance
18 on developing allowable limits from technical analyses.

19
20 NRC has developed guidance on classifying waste according to the waste classification
21 requirements. The guidance includes a BTP, "Final Waste Classification and Waste Form
22 Technical Position Papers," dated May 11, 1983, which presents guidance on classifying waste
23 (NRC, 1983d). The NRC staff has also developed guidance on acceptable methods of
24 concentration averaging in a BTP on concentration averaging and encapsulation (NRC, 1995b)
25 and recently published a revised draft for comment (NRC, 2012a). Guidance is also available in
26 Standard Review Plan 4.1 of NUREG-1200 (NRC, 1994) to assist reviewers in determining
27 whether licensees have adequate procedures to ensure that waste disposal is conducted in
28 compliance with 10 CFR 61.55 and 10 CFR 61.56.

29 **9.1.1.3** ***Insignificant Radionuclides***

30
31 Licensees may choose not to develop limits for radionuclides that contribute, in aggregate, a
32 projected dose of no greater than 10 percent of the limits prescribed in the performance
33 objectives. That is, the sum of the contributions from all radionuclides considered insignificant
34 should be no more than 10 percent of the limit for a particular performance objective. However,
35 radionuclides that could be excluded based on comparison to the limit for one performance
36 objective (e.g., protection of the public from releases) may need to have limits to comply with
37 another performance objective (e.g., protection of inadvertent intruders). Once a licensee has
38 demonstrated that radionuclides are insignificant, the dose from the insignificant radionuclides
39 must be accounted for in demonstrating that the performance objective is met, but insignificant
40 radionuclides may be excluded from further detailed evaluation in the technical analyses.

41
42 When radionuclides are considered insignificant and eliminated from further consideration,
43 licensees should justify the decision to consider them insignificant. However, licensees should
44 be aware that these decisions may need to be revisited if warranted by new information. For
45 instance, if a disposal facility proposes to accept new waste streams with significantly different
46 radionuclide inventories than previously considered, the licensee may need to assess whether
47 radionuclides that were previously considered insignificant continue to remain so. Further, if a
48 licensee obtains updated information suggesting that its understanding of the behavior of a

1 radionuclide in the site environment has significantly changed, they should reassess the
2 significance of the radionuclide to meeting the performance objectives.

3 **9.1.1.4 Application of Allowable Limits**
4

5 In general, licensees will need to develop the allowable limits on a radionuclide-by-radionuclide
6 basis. Because the performance objectives are based on the total contribution of all
7 radionuclides to the dose limits, licensees will need to perform a sum-of-fractions calculation to
8 demonstrate the allowable limits are met. Sum-of-fractions calculations are also performed for
9 waste classification under 10 CFR 61.55(a)(7). In general form, licensees can use the following
10 relationship to sum the ratio of the activity to its corresponding allowable limit for each
11 radionuclide present in the waste:
12

$$\sum_{i=1}^N \frac{Activity_i}{Limit_i} \leq 1 \quad (9.2)$$

13 where
14

15 Activity_{*i*} is the total activity [Bq] or activity concentration [Bq/m³ (Ci/m³) or Bq/g (Ci/g)] of
16 radionuclide *i*; and
17

18 Limit_{*i*} is the allowable limit [Bq (Ci), Bq/m³ (Ci/m³) or Bq/g (Ci/g)] of radionuclide *i* from
19 the most restrictive scenario used to demonstrate the performance objectives
20 would be met.
21
22

23 Licensees should also develop a mechanism to report the inventory that has been disposed of
24 and identify when action may be needed. Types of actions that could be taken may include the
25 following:
26

- 27 • Notify the regulator that a certain percentage of the allowable limit has been received.
- 28 • Evaluate whether any updates to the technical analyses are needed.
- 29 • Update the technical analyses (establish new allowable limits).
- 30 • Modify the disposal facility design, including acceptable wasteforms (see Section 9.1.2).
- 31 • Limit or prohibit further disposal of a certain type of waste (see Section 9.1.3).
32

33 When significant changes to the operations of the disposal facility occur, licensees should
34 consider updating the allowable limits. Some operational changes may simply require that a
35 licensee performs an assessment of the impact on the allowable limits; however, no change to
36 the allowable limits is required. Other operational changes may require the licensee to re-
37 examine the allowable limits. These changes may include, but are not limited to, a proposal to
38 receive new material, receipt of significant new information on the site characteristics or
39 engineering design, changes to intruder barriers, changes to the understanding of the
40 performance of key components of the disposal system, and updating of the technical analyses.
41 It is important for licensees to establish early in the process the criteria for updating and
42 revision. If a licensee uses a process to determine the significance of a potential change to the
43 established allowable limits, they should maintain a comprehensive list of all items that were

1 screened from impacting the allowable limits. The cumulative impact from many small changes
2 can be additive such that, in total, the allowable limits would require revision to avoid future
3 mitigation.

4
5 If a licensee revises allowable limits, they should provide regulators a clear basis for the
6 revisions that includes a side-by-side comparison of changes to parameters or models and the
7 basis for those changes. The side-by-side comparison will provide transparency for the
8 revisions and will facilitate the regulator's review of the revised allowable limits. It may also
9 have the complementary benefit of enhancing stakeholder confidence in the revisions. If limits
10 are relied upon to demonstrate defense-in-depth protections, the licensee should provide a
11 basis that defense-in-depth protections remain adequate in light of the proposed change.

12 **9.1.2 Acceptable Wasteform Characteristics and Container Specifications**

13
14 Section 61.58(a)(2) of 10 CFR Part 61 requires licensees to specify acceptable wasteform
15 characteristics and container specifications as part of the waste acceptance criteria. Acceptable
16 wasteform characteristics and container specifications, together with the other waste
17 acceptance criteria (e.g., radionuclide limits), provide reasonable assurance that the
18 performance objectives will be met and may provide defense-in-depth protections. Acceptable
19 wasteform characteristics and container specifications include properties that facilitate handling
20 of the waste at the disposal facility, promote stability of the waste to minimize subsidence and
21 water contact with the waste, minimize release and migration of the radionuclides from the
22 disposal site, deter or preclude inadvertent intrusion into the waste, or limit exposures during
23 operations.

24
25 The regulations require that all waste meet the minimum requirements specified in 10 CFR
26 61.56(a). The minimum requirements are designed to facilitate handling of waste and protect
27 the health and safety of personnel at the disposal facility. Licensees may also identify additional
28 minimum criteria to facilitate handling and protect facility personnel depending on the particular
29 operational practices and environmental conditions at a disposal facility. Additional minimum
30 criteria might include acceptable limits for waste package external surface dose rate and heat
31 generation, necessary labeling and marking to be applied to waste packages, container
32 specifications, or specific requirements for acceptance of bulk waste. Licensees should provide
33 a rationale for inclusion of the additional minimum criteria which should include a demonstration
34 that they are comprehensive. The basis, as appropriate, should identify why the additional
35 criteria were developed and include the performance objective(s) that the additional criteria
36 support and whether the criteria are considered defense-in-depth protections.

37
38 Certain waste streams will need to meet more rigorous requirements on wasteform than the
39 minimum requirements to ensure stability after disposal and demonstrate compliance with the
40 performance objectives. The requirements to ensure stability are specified in 10 CFR 61.56(b).
41 For licensees relying on the waste classification requirements to develop waste acceptance
42 criteria, Class B and Class C waste must meet the requirements to ensure stability. Licensees
43 developing waste acceptance criteria from the results of the technical analyses will need to
44 identify the wastes that will need to meet stability requirements.

45
46 Licensees may demonstrate that the stability requirements would be met by using one or more
47 of the following approaches - a stable wasteform, a container that provides stability, or facility
48 design. The approach, or combination of approaches, that a licensee uses to demonstrate

1 stability will determine the waste acceptance criteria needed to ensure stability and defense-in-
2 depth protections. For example, if a licensee constructs a reinforced concrete vault and
3 demonstrates that it provides adequate stability for the required timeframe, the waste
4 acceptance criteria may not need to address stable wasteforms or container specification for
5 stability. In general, stable wasteforms or container specifications for stability are necessary
6 when degradation of the waste may significantly affect meeting the performance objectives. For
7 example, stable wasteforms or containers would be necessary for wasteforms with sufficient
8 radioactivity such that its release from the disposal site would significantly affect public health
9 and safety. Likewise, stable wasteforms may be necessary for higher activity waste to minimize
10 exposures to inadvertent intruders since stable wasteforms tend to provide a recognizable and
11 non-dispersible waste.

12
13 Licensees should provide a technical basis for the criteria for allowable wasteform
14 characteristics and container specifications. Licensees relying on the waste classification
15 requirements to develop waste acceptance criteria may use the requirements of 10 CFR 61.56
16 as a basis. Licensees developing waste acceptance criteria from the results of the technical
17 analyses should clearly identify how the acceptable wasteform characteristics and container
18 specifications are consistent with the assumptions, modeling approaches, and results of the
19 technical analyses. The basis, as appropriate, should also identify which performance
20 objective(s) the criteria support and whether the criteria provide defense-in-depth protections.
21 Further, the basis should identify the time period over which the criteria are intended to protect
22 public health and safety. For example, some acceptable wasteform characteristics may only
23 need to be relied upon to protect facility personnel during operations; other acceptable
24 wasteform characteristics may be important to protect the general population from releases of
25 radioactivity from longer-lived waste or intruders from inadvertent exposures to longer-lived
26 waste farther into the future. The criteria should provide reasonable assurance that the
27 longevity required of the wasteform and container capabilities is and can be adequately
28 demonstrated. In some cases this may involve criteria to document traditional engineering tests
29 or specifications for waste containers. In other cases, the criteria may be more rigorous and
30 include laboratory testing, predictive modeling, or comparison to analogs. In still other
31 instances, the duration of time that stability of the wasteform or containers is required may be so
32 long that the uncertainty in material behavior may preclude a reasonable demonstration of
33 stability. In these instances, licensees should not solely rely upon wasteform characteristics or
34 container specifications to ensure safety. Rather, other limits or defense-in-depth protections
35 may need to be imposed such as allowable limits.

36
37 NRC has developed guidance in the form of a BTP (NRC, 1991b) for waste generators on
38 wasteform test methods and results that are considered acceptable for complying with the
39 10 CFR Part 61 stability requirements. The guidance also identifies conditions that stable
40 wasteforms should meet to demonstrate that the stability requirements are met. The guidance
41 is applicable for licensees who develop waste acceptance criteria from the 10 CFR Part 61
42 waste classification requirements. The guidance is also considered generally applicable to
43 licensees who develop waste acceptance criteria from the results of the technical analyses
44 required in 10 CFR 61.13. However, there may be specific cases where the approaches need
45 to be amended due to site-specific conditions. In these cases, licensees should provide a
46 technical basis for the divergence from the BTP on wasteform test methods (NRC, 1991b).
47 Licensees may also consult IAEA-TECDOC-864 (IAEA, 1996), which provides considerations
48 for establishing container specifications. Section 3.2.4 of this document provides guidance
49 associated with wasteforms.

1
2 Reviewers should coordinate reviews of the acceptable wasteform characteristics and container
3 specifications with the reviews of the technical analyses required to meet 10 CFR 61.13 (see
4 Sections 3.2.4, 4.3, and 8.0). Reviewers should verify that the licensee's proposed criteria for
5 wasteform characteristics and container specifications are reasonably consistent with the
6 wasteforms and containers assessed in source terms for the performance assessment and
7 intruder assessment, as well as assessments of expected and accidental occupational
8 exposures during handling storage, and disposal of waste. In other words, licensees should
9 establish criteria for wasteforms and containers that ensure the wasteforms and containers will
10 provide the expected performance relied upon in the technical analyses including defense-in-
11 depth capabilities.

12
13 In general, reviewers should focus their review of wasteform characteristics and container
14 specifications on waste streams that are expected to contribute most significantly to risk to the
15 public, workers, and the environment. The significant wasteform characteristics and container
16 specifications are likely to vary depending upon the disposal site characteristics and engineering
17 design. Reviewers should evaluate the licensee's technical analyses to understand which
18 wasteform characteristics and container specifications are important for demonstrating that the
19 performance objectives are met. These may include mechanical properties to ensure stability or
20 limit the likelihood or consequences of potential accidents during operations. They may also
21 include durability or leaching characteristics to minimize releases to the general environment.
22 Further, reviewers should evaluate whether the allowable wasteform characteristics and
23 container specifications would significantly affect the stability of the disposal site after closure.
24 For example, reviewers may need to evaluate whether waste containers could withstand
25 anticipated mechanical loads after disposal. Reviewers should coordinate their review of the
26 development of acceptable wasteform characteristics and container specifications with their
27 review of allowable limits from the technical analyses (see Section 9.1.1.1).

28
29 Reviewers should also evaluate whether the technical basis provided for each criteria will
30 provide assurance that all the performance objectives will be met. For example, if a particular
31 wasteform characteristic or container specification is based on the results of the performance
32 assessment, reviewers should confirm that the limit would not preclude licensees from
33 demonstrating that the other performance objectives (e.g., protection of inadvertent intruders via
34 the intruder assessment) are also met. Reviewers should also evaluate whether the criteria
35 ensure that the wasteform characteristics and container specifications are expected to persist
36 for the duration needed to demonstrate compliance with the performance objectives. Reviewers
37 may elect to conduct independent analyses to inform the review.

38 **9.1.3 Restrictions or Prohibitions**

39
40 Section 61.58(a)(3) of 10 CFR Part 61 requires licensees to specify restrictions or prohibitions
41 on waste, materials, or containers that might affect meeting the performance objectives.
42 Licensees should identify any specific radionuclides, chemical or hazardous materials, or
43 specific containers or types of containers that are restricted or prohibited from acceptance at the
44 facility. The restrictions and prohibitions should adequately reflect those identified in the
45 minimum waste characteristic requirements specified in 10 CFR 61.56(a).

46
47 Reviewers should assess the licensee's list of restrictions or prohibitions to ensure it is
48 comprehensive and adequately considers the minimum waste characteristics requirements

1 specified in 10 CFR 61.56(a). Reviewers should also assess whether the licensee's list is
2 consistent with the assumptions, modeling approaches, and results of the technical analyses
3 used to demonstrate that the performance objectives would be met. Reviewers may perform
4 independent modeling to assist this review.

5 **9.2 Waste Characterization Methods**

6
7 Licensees are required, per 10 CFR 61.58(b), to provide methods for characterizing waste for
8 acceptance. The methods shall identify the parameters to be characterized and the level of
9 uncertainty in the characterization data that is considered acceptable. The regulations specify
10 that, at a minimum, the following information must be required to adequately characterize waste
11 for acceptance:

- 12
13 • **Physical and chemical characteristics.** Information on the physical and chemical
14 characteristics of the waste support handling, the determination of compatibility with the
15 container and other waste, as well as any potential treatment or conditioning processes.
16 Physical characteristics may include a description of the material including its density,
17 consistency, and appearance. Chemical characteristics may include pH, reactivity,
18 chemical compounds present, and the presence of hazardous or toxic constituents.
19
20 **Volume, including the waste and any stabilization or absorbent media.** Information
21 on volume supports waste handling decisions. The information is also important to
22 determine or verify the concentration of radionuclides for comparison with the waste
23 acceptance criteria. Volume information should include container volume, actual waste
24 volume, and the container utilization factor. The container utilization factor represents
25 the portion of the container value that is filled with waste, including stabilization or
26 absorbent media. Information on the container volume should represent the volume of
27 the disposal site that will be occupied by the container. Information on the actual waste
28 volume should include stabilization or absorbent media. If used, stabilization or
29 absorbent media should be identified.
30
- 31 • **Weight of the container and contents.** Information on weight should include container
32 weight (or mass) that would have to be handled. Weight information may be important
33 for meeting stability criteria as well as transportation requirements. This information is
34 also important to determine or verify the concentration of radionuclides for comparison to
35 the waste acceptance criteria.
36
- 37 • **Identities, activities, and concentrations of radionuclides.** This information may
38 include the total activity in a container, the identities and activities of the significant
39 radionuclides per unit volume or mass, radiation dose levels at the surface of the
40 container, and external contamination levels on the surface of the container. Significant
41 radionuclides are primarily those that affect the demonstration that the performance
42 objectives would be met. Significant radionuclides also include radionuclides important
43 for waste classification.
44
- 45 • **Characterization date.** The characterization date helps determine the validity of the
46 characterization documentation.
47

- 1 • **Generating source.** Identification of the generating source helps determine the validity
2 of the characterization documentation. Information on the generating source may
3 include packaging date, generator site, location of the process which generated the
4 waste, and information on conditioning, if applicable.
5
- 6 • **Any other information needed to characterize the waste to demonstrate that the**
7 **waste acceptance criteria are met.** This information includes any additional data
8 about the waste that are important to the facility's ability to protect public health and
9 safety. This information should be identified from waste acceptance criteria which are
10 drawn from either the results of the technical analyses that are used to demonstrate that
11 the performance objectives or the waste classification requirements are met. For
12 example, data on mechanical properties of wasteforms or containers may be needed to
13 ensure that any criteria for stability, as necessary, can be met.
14

15 The purpose of these requirements is to ensure that knowledge of the waste's characteristics is
16 (1) commensurate with the assumptions and approaches employed in the technical analyses
17 used to develop the proposed waste acceptance criteria and is, thus, (2) sufficient to
18 demonstrate that the waste acceptance criteria are met.
19

20 For waste acceptance criteria developed from the waste classification requirements specified in
21 10 CFR 61.55, waste characterization methods should be commensurate with the assumptions
22 and approaches employed to develop the waste classification requirements. For waste
23 acceptance criteria developed from the technical analyses, waste characterization methods
24 should be consistent with the approaches employed in the analyses. In other words, for each of
25 these two approaches to develop waste acceptance criteria, there will have been assumptions
26 and approaches employed to derive the criteria. The methods should ensure that significant
27 assumptions or approaches are characterized sufficiently to provide assurance that the criteria
28 can be met. For example, the limits for Class B and C waste, per the 10 CFR 61.55 waste
29 classification requirements, were developed from an analysis that assumed Class B and C
30 waste would be stable. As a result, 10 CFR Part 61 includes requirements that Class B and C
31 waste must be disposed in a stable form. Therefore, licensees may need to specify waste
32 acceptance criteria to ensure that Class B and C waste are stable. In this example, licensees
33 would also need to specify acceptable methods to characterize the waste to demonstrate that
34 the stability criteria will be met.
35

36 Regardless of the method used to develop waste acceptance criteria, licensees should specify
37 acceptable methods to characterize waste, criteria for determining an acceptable level of
38 uncertainty in the characterization data, and documentation required to ensure sufficient detail is
39 available to demonstrate that the waste acceptance criteria of the land disposal facility are met.

40 **9.2.1 Acceptable Waste Characterization Methods**

41

42 Licensees shall specify methods for adequately characterizing waste for the purposes of
43 demonstrating that the disposal facility's waste acceptance criteria are met. These
44 specifications should identify methods for characterizing the radionuclide content of the waste,
45 as well as any significant waste characteristics and container specifications. The intent of the
46 methods should be to ensure that generators provide reasonably realistic representations of the
47 radionuclide content of their waste and the necessary waste characteristics for comparison with
48 the waste acceptance criteria. In general, the characterization methods would be specific to

1 each individual waste stream, and would consider the different radiological and other
2 characteristics of the waste streams destined for disposal at a land disposal facility. Ideally, the
3 disposal facility operator should ensure that the generator's characterization is near in time to
4 the demonstration that waste meets the acceptance criteria. When proximate characterization
5 is not possible and the time interval from characterization to disposal may significantly affect
6 meeting the waste acceptance criteria, the disposal facility operator should ensure that a basis
7 supports why earlier characterization remains acceptable for demonstrating that the waste
8 acceptance criteria are met. IAEA has developed guidance on strategies and methodologies for
9 radioactive waste characterization that licensees may find applicable to develop acceptable
10 waste characterization methods (IAEA, 2007).

11 **9.2.1.1 Acceptable Methods for Characterizing Activities and Concentrations**

12
13 The first step in characterizing the waste to meet the waste acceptance criteria is to determine
14 the activities and concentrations of significant radionuclides in the waste. Licensees may use a
15 variety of methods to determine radionuclide activities or concentrations in LLW. Acceptable
16 methods would likely include either direct measurement of individual radionuclides or indirect
17 methods that infer activities or concentrations of radionuclides from other measurements or
18 knowledge of the waste to enhance confidence that the waste acceptance criteria are met.
19 These methods are described in more detail in the BTP on radioactive waste classification and
20 wasteforms (NRC, 1983d).

21
22 Direct measurement of individual radionuclides generally provides the most confidence that the
23 allowable activities and concentration limits identified in the waste acceptance criteria are met.
24 However, the NRC staff recognizes that direct measurement may not always be necessary or
25 warranted. For example, activities or concentrations of certain radionuclides may be overly
26 difficult to measure with current technology (e.g., below minimum detection capabilities) or
27 personnel safety considerations may limit direct measurement of specific waste streams. In
28 these cases, licensees are permitted to accept other methods (e.g., indirect or material
29 accountability methods) to demonstrate that the allowable limits are met.

30
31 Indirect methods infer radionuclide activities or concentrations from a number of approaches
32 which include materials accountability, characterization by source, and the use of scaling
33 factors. Radionuclide material accountability relies on inferences from the difference between
34 the quantity of radioactive material entering and exiting a given process. Characterization by
35 source is similar to material accountability and involves determining the radionuclide content
36 through knowledge and control of the source of the waste. Indirect methods often rely on the
37 use of scaling factors to relate the inferred activity or concentration of one radionuclide to
38 another radionuclide or gross radioactivity that is measured.

39
40 Indirect methods may be appropriate to determine activities or concentrations of difficult-to-
41 measure radionuclides provided there is reasonable assurance that the indirect methods can be
42 correlated with actual measurements. Licensees should require that generators develop
43 correlations between measured or known quantities and the inferred quantity on a generating
44 facility and waste stream basis. NRC guidance on the use of indirect methods to determine the
45 inventory of radionuclides will be summarized in a Regulatory Issue Summary in 2015. The
46 BTP on radioactive waste classification provides additional guidance on acceptable uses of
47 indirect methods for use in waste classification (NRC, 1983d). This guidance may also be
48 useful for identifying methods to demonstrate that the allowable limits developed from technical

1 analyses are met. Licensees should also consider the issues identified by the NRC staff in
2 *Information Notice 86-20* (NRC, 1986b) when specifying criteria for application of indirect
3 methods to meeting the allowable limits. Further, NUREG/CR-6567 (NRC, 2000b) and IAEA
4 (2009) provide information on scaling factors that licensees may wish to consider when
5 identifying criteria for the use of indirect methods. Although previous NRC guidance is focused
6 on determining concentrations for demonstrating compliance with allowable limits developed
7 from the waste classification requirements of 10 CFR Part 61, they may also be applicable, on a
8 case-by-case basis, for determining limits for demonstrating that allowable limits developed from
9 the technical analyses are met. Land disposal facility operators should require generators to
10 provide information as part of certification that details how scaling factors are derived and
11 whether periodic re-analysis of the scaling factors resulted in a revision to the scaling factors. If
12 a generator determines that scaling factors need to be revised, a determination should be made
13 whether the revision affects previous shipments of waste to the facility. Land disposal facility
14 operators should assess any impacts to acceptable inventories, both previous disposals and
15 future acceptable waste acceptance criteria that may result from revisions to scaling factors.
16

17 Each of these methods is subject to various sources of uncertainty (Figure 9-5), including, but
18 not limited to, the following:

- 19 • a sample's degree of representativeness of the whole, due to temporal and spatial
20 variability in:
 - 21 – concentrations of directly sampled radionuclides
 - 22 – samples used to establish scaling factors
 - 23 – samples used to establish concentrations of process inputs
- 24 • analytical uncertainty in sampled radionuclides
- 25 • uncertainty in dose rate scans
- 26 • uncertainty in any scaling factors for unsampled containers
- 27 • uncertainty in radionuclide concentrations in inputs and input volumes, if the radionuclide
28 concentrations in the product are based on the inputs and are not independently
29 measured

30 9.2.1.1.1 *Characterization Methods for Criteria Based on the Waste Classification* 31 *Requirements* 32

33 The BTP on radioactive waste classification and wastefoms provides guidance on the use of
34 various methods to determine concentrations to demonstrate that allowable concentrations
35 developed from the 10 CFR Part 61 waste classification requirements are met (NRC, 1983d).
36 The BTP indicates that the NRC staff considers a reasonable target for determining measured
37 or inferred radionuclide concentrations to be that concentrations are accurate to within a factor
38 of 10. However, more precision may be required in certain cases to demonstrate that the
39 performance objectives will be met. In general, licensees should reflect uncertainty in
40 radionuclide activities and concentrations in the technical analyses.

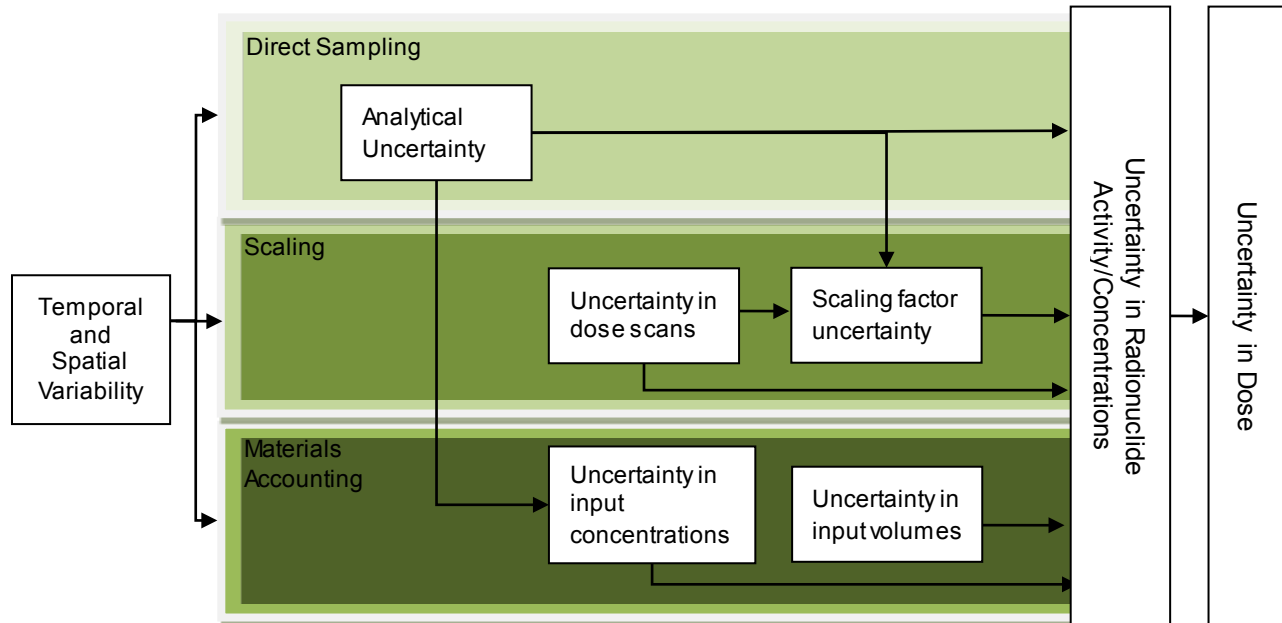


Figure 9-5 Sources of Uncertainty in Various Methods of Determining Radionuclide Activities or Concentrations in Waste Packaged for Disposal

1
 2 Section 61.55(a)(8) of 10 CFR Part 61 provides acceptable methods for determining
 3 radionuclide concentrations for comparison with allowable activities and concentrations that are
 4 developed from the waste classification requirements. A licensee may average the
 5 concentration of a radionuclide over the volume of the waste, or the weight of the waste, if the
 6 concentration units are expressed as nanocuries per gram. The NRC staff has developed
 7 guidance on acceptable methods of concentration averaging in a BTP on concentration
 8 averaging and encapsulation (BTP CA) (NRC, 1995b) and recently published a revised draft for
 9 comment (NRC, 2012a). The revised draft BTP CA is based on many of the same methods for
 10 performing an intruder assessment that were used to develop this guidance.

11
 12 For example, the revised draft BTP CA considers the intruder receptor scenarios described in
 13 Section 4.3.1.1 of this document in developing guidance on acceptable averaging approaches
 14 (NRC, 2012a). However, the revised draft BTP CA also considers receptor scenarios in which
 15 an individual may be exposed to discrete items (NRC, 2012a). For instance, the NRC staff
 16 considered a waste-handling receptor scenario to develop the revised draft BTP CA for disposal
 17 of discrete sources, which is not discussed in this guidance for intruder assessments (NRC,
 18 2012a). The NRC staff used these receptor scenarios to develop the revised draft BTP CA for
 19 limiting the range of waste concentrations that can be mathematically averaged in a single
 20 container, as well as specific guidance on appropriate waste volumes over which concentrations
 21 should be averaged for waste classification by waste generators or processors (NRC,
 22 2012a). This guidance—as opposed to the guidance in the revised draft BTP CA (NRC,
 23 2012a)—focuses on determining appropriate concentrations to use in site-specific intruder
 24 analyses performed by land disposal facility licensees. Irrespective of any concentration
 25 averaging used to determine waste classification, radionuclide concentrations should be
 26 representative of the actual waste distribution (see Section 4.3.2.2.2 of this guidance), although
 27 conservative assumptions are, in general, appropriate.

1 **9.2.1.1.2** *Characterization Methods for Criteria Based on the Results of the Technical*
2 *Analyses*
3

4 Licensees developing waste acceptance criteria from the results of the technical analyses must
5 identify acceptable methods for characterizing the waste to demonstrate that the waste
6 acceptance criteria are met. The appropriate method for characterizing the waste will depend
7 on the specific parameter being measured, the hazards associated with acquiring the
8 information, and the amount and quality of the data needed to adequately characterize the
9 waste.

10
11 The specific parameters and the quantity and quality of the data should be consistent with the
12 intended use of the information, namely to demonstrate that the waste acceptance criteria are
13 met. In this case, the criteria are developed from the results of the technical analyses.
14 Therefore, the parameters and the data developed to characterize the parameters should be
15 consistent with the analyses. In other words, characterization parameters should focus on
16 those parameters of the analyses which are significant for a licensee's demonstration that the
17 performance objectives are met and that defense-in-depth protections are provided. Licensees
18 should identify significant parameters of the analyses as criteria for waste acceptance.
19 Likewise, the quantity and quality of data should be commensurate with the parameter's
20 importance to meeting the performance objectives. Licensees may use a graded approach in
21 defining the level of quality for the data. Therefore, characterization data for parameters that
22 are more significant for demonstrating that the performance objectives would be met should
23 generally require more robust pedigree than data for parameters of lesser significance.
24 Likewise, characterization data for parameters that are considered defense-in-depth protections
25 should generally require more robust pedigree than data for parameters that are not relied upon
26 for defense-in-depth.

27
28 As discussed in Section 9.2.1.1, adequate waste characterization may include a combination of
29 both direct and indirect methods. Direct methods may include sampling and laboratory analysis
30 as well as certain non-destructive evaluation techniques. Indirect methods may use non-
31 destructive evaluation techniques as well as acceptable knowledge to supplement or provide
32 data that might otherwise be collected by direct methods. The BTP on radioactive waste
33 classification provides guidance on the use of various methods to determine concentrations to
34 demonstrate that allowable concentrations developed from the 10 CFR Part 61 waste
35 classification requirements are met (NRC, 1983d). The revised draft BTP CA is also available
36 to licensees (NRC, 2012a). The methods discussed in these documents may also be
37 appropriate for use in characterizing waste for meeting waste acceptance criteria developed
38 from the results of the technical analyses. Licensees should provide a basis for inclusion or
39 exclusion of the methods discussed in the BTP on radioactive waste classification and
40 wasteform (NRC, 1983d) for characterizing data to meet waste acceptance criteria developed
41 from the results of the technical analyses. The basis should include either a description of why
42 the method from the BTP on radioactive waste classification and wasteform (NRC, 1983d) is
43 appropriate or inappropriate depending upon whether it is included or excluded.

44 **9.2.1.2** *Acceptable Methods for Characterizing Wasteform and Containers*
45

46 Section 61.56 of 10 CFR Part 61 specifies requirements for waste characteristics, which apply
47 to all waste classes, as well as stability requirements, which are required only for Class B and C
48 wastes because of their higher radioactivity. Waste stability helps to limit inadvertent intrusion

1 exposures and minimize water infiltration into the disposal units. Wastes that are stable, and
2 thus recognizable after the active institutional control period has ended, ensure that the impacts
3 of inadvertent intrusion remain limited to discovery-type receptor scenarios. To the extent
4 practical, Class B and C wastes should maintain their gross physical properties and identity over
5 a 300-year period to be consistent with the concepts in 10 CFR 61.7(b)(2). However, certain
6 waste may need to meet the stability requirements for longer periods of time in order for a
7 licensee to demonstrate that the performance objectives would be met.

8
9 The NRC staff has developed guidance on wasteforms to comply with waste characteristic
10 requirements in its BTP on wasteforms (NRC, 1991b). The guidance also applies to Class A
11 waste that is not segregated from Class B and C wastes. Additional requirements, specified as
12 license conditions, may be necessary for waste, including that categorized as Class A by
13 10 CFR 61.55(a)(6). Regulators can specify additional requirements in license conditions based
14 on the need to mitigate potential exposures as demonstrated in the technical analyses.

15
16 Licensees should specify methods for characterizing the wasteform and container.
17 Characterizing the waste to demonstrate that acceptable wasteform characteristics and
18 container specifications are met is generally a two-staged process. First, the licensee should
19 require generators to define the wasteform characteristics and container attributes, which
20 includes performance data (e.g., compressive strength, load bearing capability, resistance to
21 impact, corrosion, fire resistance, etc.). The disposal facility operator should identify which
22 quality-related parameters need to be controlled, including any necessary details of the
23 arrangements for controlling them, in order to provide confidence that the acceptance criteria
24 are met. Second, the licensee should require that generators confirm that the wasteform or
25 container conforms to the applicable specifications. The disposal facility operator should ensure
26 that the generator's confirmation of the applicable specifications meets the quality requirements
27 for the characterization. In some instances, this may include the timeliness of the generator's
28 confirmation. For instance, if a waste container's structural stability is important (e.g., a
29 defense-in-depth protection) and the waste is planned to be stored for extended periods prior to
30 shipment for disposal, the environment in which it is stored may need to be controlled to ensure
31 that an earlier characterization of the container's stability is adequate to meet the acceptance
32 criteria at the time of disposal.

33 **9.2.2 Data Quality Objectives Process**

34
35 Demonstrating that the waste acceptance criteria are met is a process that is supported by
36 waste characterization data. For most waste, this decision is supported by statistical tests
37 based on the results of one or more direct samples. The initial assumption, or null hypothesis,
38 that a licensee should use is that each parameter to be characterized exceeds the allowable
39 limits specified in the waste acceptance criteria. The characterization should be designed to
40 provide information to reject this initial assumption. The NRC staff recommends that licensees
41 use the Data Life Cycle as a framework for planning, implementing, and evaluating
42 characterization results prior to making a decision. Licensees and generators should coordinate
43 to apply the framework or a similar methodology to the waste characterization activities. Figure
44 9-6 summarizes the major activities associated with each phase of the Data Life Cycle for waste
45 characterization.

- 1 One aspect of the planning phase of the Data Life Cycle is the Data Quality Objectives (DQOs)
 2 process. The DQO process is a series of seven planning steps for establishing criteria for data
 3 quality and developing characterization plans:
- 4 1. State the problem;
 - 5 2. Identify the goals of the study;
 - 6 3. Identify inputs to the decision;
 - 7 4. Define the study boundaries;
 - 8 5. Develop the analytic approach;
 - 9 6. Specify performance or acceptance criteria; and
 - 10 7. Develop the plan for obtaining data
- 11

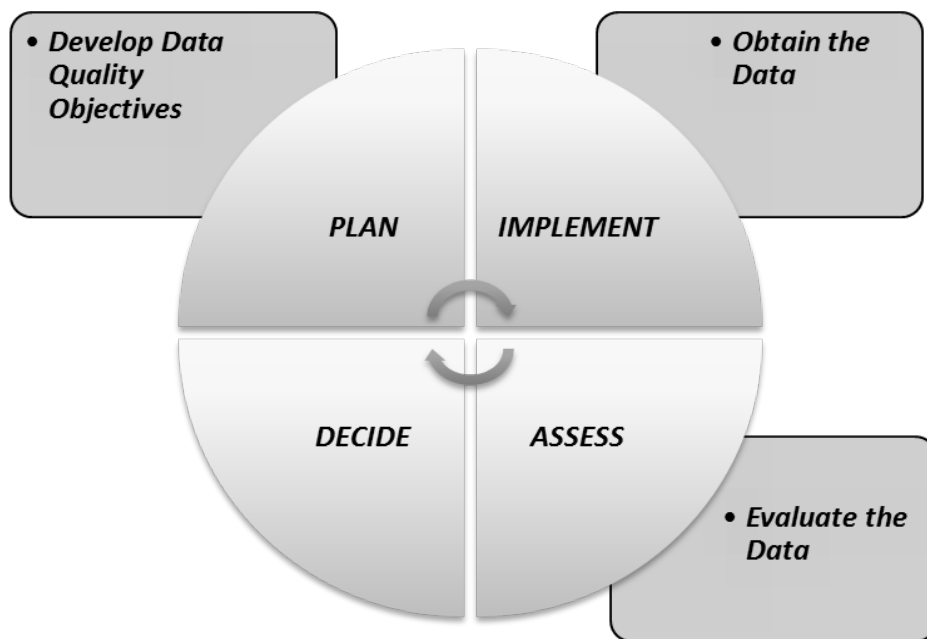


Figure 9-6 Data Life Cycle Framework for Waste Characterization

12 The process should use a graded approach to data quality requirements. A graded approach is
 13 one in which the level of effort required to develop data quality objectives should be
 14 commensurate with the importance of the data for demonstrating that the performance
 15 objectives would be met. This approach facilitates more effective characterization planning with
 16 consideration of how the data will be used. Thus the process should be a flexible planning tool
 17 that can be varied from simple to complex depending on the specific situation.

18
 19 DQOs should be qualitative or quantitative statements that satisfy all of the following:

- 21 • Clarify the characterization objective;
- 22 • Define the most appropriate type of data to collect;
- 23 • Determine the most appropriate conditions for collecting the data; and
- 24 • Specify limits on decision errors that will be used as the basis for establishing the
 25 quantity and quality of data needed to demonstrate the waste acceptance criteria are
 26 met.

1 Using the DQO process can help ensure that the type, quantity, and quality of data will be
2 appropriate to determine that the waste acceptance criteria are met. Additional guidance on the
3 Data Life Cycle and Data Quality Objectives process is provided in an EPA guidance report
4 (EPA, 2006). The *Multi-Agency Radiation Survey and Assessment of Materials and Equipment*
5 (NRC, 2009) provides guidance for applying the Data Life Cycle to disposition surveys of
6 materials and equipment to ensure the surveys are adequate to meet the disposition
7 requirements. Likewise, the *Multi-Agency Radiation Laboratory Analytical Protocols Manual*
8 (NRC, 2004b) provides guidance for the application of the Data Life Cycle to projects that
9 require the laboratory analysis of radionuclides to ensure that the laboratory data will meet the
10 data requirements. These guidance documents may be useful to licensees to develop data
11 quality objectives for generator characterization data that demonstrates the waste acceptance
12 criteria are met.

13 **9.2.3 Documentation**

14
15 Licensees should require waste generators to provide sufficient waste characterization
16 documentation to ensure that the waste is adequately characterized to demonstrate that the
17 acceptance criteria are met. The level of documentation that licensees require may vary across
18 the waste streams accepted for disposal depending on both the complexity of the waste
19 streams and the importance of the waste streams to demonstrating that the performance
20 objectives are met or that defense-in-depth protections are provided. The elements of the
21 documentation should typically include the following:
22

- 23 • **Organization and Responsibilities.** Organizations and personnel responsible for
24 waste characterization should be identified. Personnel responsible for collecting and
25 managing characterization data should be properly trained to recognize the significance
26 of the data. Qualifications of personnel should be included to provide assurance that the
27 data are properly collected and managed. For instance, acceptable methods for waste
28 characterization may specify the use of a certified laboratory. In this case, the
29 documentation should include the laboratory's accreditation.
30
- 31 • **Quality Assurance.** Waste characterization data should be collected according to an
32 acceptable QA program. The documentation should identify the QA program. Standard
33 Review Plan 9.1 of NUREG-1200 provides guidance on acceptable QA programs (NRC,
34 1994).
35
- 36 • **Procedures.** Procedures formalize the process for characterizing the waste. The
37 procedures should describe the steps followed to characterize the waste as well as the
38 administrative processes for ensuring the type, quantity, and quality of data is
39 appropriate to adequately characterize the waste. Procedures should include processes
40 for sampling, packaging, transportation, laboratory analysis, and data control, as
41 appropriate. Standard Review Plan 8.6 of NUREG-1200 provides additional guidance
42 on administrative and operating procedures (NRC, 1994).
43
- 44 • **Records.** Waste characterization records should include those that are necessary to
45 meet the disposal facility's waste acceptance criteria as specified by the waste
46 certification program (see Section 9.3). Records that contain characterization
47 procedures, data, and specifications, including the QA program, should be controlled
48 documents that are subject to review, approval, and distribution procedures, as well as a

1 process for making revisions. Existing record control programs may be adequate to
2 provide the necessary controls.

3 **9.3 Waste Certification Program**

4
5 Licensees, per 10 CFR 61.58(c), must develop a program to certify that waste meets the
6 acceptance criteria prior to receipt at a disposal facility. Certification of waste also provides
7 assurance that a disposal facility operates within the limits established to demonstrate that the
8 10 CFR Part 61 performance objectives would be met. Once certified to meet a disposal
9 facility's waste acceptance criteria, waste must then be managed to maintain its certification
10 until its emplacement in a disposal unit.

11
12 The regulations specify that the certification program must:

- 13
- 14 • Designate the authority to certify and receive waste for disposal at the disposal facility;
- 15 • Provide procedures for certifying that waste meets the waste acceptance criteria;
- 16 • Specify documentation required for waste characterization, shipping and certification;
- 17 • Identify records, reports, tests, and inspections that are necessary to maintain and
18 provide criteria for auditing; and
- 19 • Provide approaches for managing certified waste to maintain its certification status.

20 **9.3.1 Certification Program**

21
22 Licensees should develop a certification program that defines administrative procedures to
23 provide assurance that waste and its packaging meets the waste acceptance criteria of the
24 disposal facility prior to receipt of the waste at the disposal facility. The program should also
25 provide a traceable and verifiable record of and basis for certification. The certification program
26 should address the following questions:

- 27
- 28 • Who is responsible for certifying that waste is acceptable for disposal and what are their
29 required qualifications?
- 30 • How and when shall waste be certified as acceptable for disposal?
- 31 • What documentation is required to provide a traceable and verifiable record for
32 certification and how will certification be audited?
- 33 • How shall waste that has been certified be managed to maintain its certification?
- 34

35 The following sections provide guidance on information to adequately address these questions
36 in order to meet the requirements of 10 CFR 61.58.

37
38 The principal documents that constitute the certification program should be subject to controls.
39 Therefore, the certification program should identify which documents are to be controlled such
40 as the waste certification program description, certification procedures, and QA program
41 documentation. Document control includes review and approval, distribution to designated
42 recipients, and a controlled process for making revisions to the documents. Existing document
43 control programs at a disposal facility may provide the necessary controls for the documents
44 that are part of the waste certification program.

1 **9.3.1.1 Organizations and Responsibilities for Certification**
2

3 The land disposal facility operator is responsible for developing the requirements of and
4 managing the certification program. Waste certification is typically performed by the waste
5 generator because they are the most knowledgeable about the waste and can most effectively
6 characterize it as it is generated. As waste progresses toward disposal, characterization to
7 meet the acceptance criteria can become more challenging and expensive to perform.
8 However, in some cases, such as an infrequent generator of small quantities of waste, a waste
9 collector, processor, or the land disposal facility operator may be more qualified to perform the
10 certification on behalf of the generator. The organization responsible for certification must
11 certify that waste is acceptable for disposal at the land disposal facility according to the disposal
12 facility's waste certification requirements and obtain authorization from the land disposal facility
13 operator to transfer the waste for disposal.

14
15 A certification program must identify the designated individuals or organizations that are
16 responsible for the certification process. These designees include representatives of the land
17 disposal facility who are responsible for managing the certification program, and representatives
18 of organizations responsible for complying with the land disposal facility's certification program
19 to certify that the waste meets the acceptance criteria. These individuals or organizations may
20 include waste generators, waste collectors, waste processors, the land disposal facility operator,
21 or other organizations or individuals qualified to certify that the waste meets the acceptance
22 criteria. The program should require that personnel who are designated to certify waste be
23 identified, qualified, and approved by the disposal facility operator's designated authority.

24
25 The certification program should also identify the training requirements needed for the various
26 individuals who are involved in the program. At a minimum, the program should require training
27 of the official who certifies that the waste meets the acceptance criteria of the disposal facility.
28 In addition, individuals should be trained in the procedures that control the part of the
29 certification process with which they are involved.

30 **9.3.1.2 Certification Procedures**
31

32 Licensees should implement the certification program through the use of documented
33 processes and procedures. The certification program should formalize the processes and
34 procedures for certifying waste and for maintaining certification until the waste is emplaced in a
35 disposal unit.

36
37 The procedures should describe the administrative process that designated certification officials
38 should follow to ensure that waste is certified prior to receipt at the land disposal facility. The
39 procedures should require a signed statement certifying that the waste meets the disposal
40 facility's waste acceptance criteria and, therefore, is acceptable for disposal. The signature on
41 the certification statement confirms that the waste has been characterized adequately and
42 necessary shipping requirements have been met.

43
44 Waste must be certified prior to shipment to the disposal facility. This requirement ensures that
45 the waste certification program is effective in preventing the transfer of waste that does not meet
46 the waste acceptance criteria of the disposal facility. The requirement also prevents potential
47 hazards associated with managing the waste rejected by the disposal facility to which it is
48 transferred. Requiring certification before waste is transferred also reduces the likelihood of

1 having to recall a waste shipment due to a discovery by the certification official, after the waste
2 is in transit, that the waste does not comply with the waste acceptance criteria. Certification that
3 the waste is ready for transfer and meets the waste acceptance criteria and the applicable
4 transportation regulations is a control point in the transfer process. The procedures controlling
5 waste transfer should not allow transfer to occur unless the certification statement has been
6 signed. Once signed, the certification statement becomes part of the record for the transfer of
7 the waste. Once the waste is certified as acceptable for disposal, the land disposal facility can
8 authorize transfer of the waste for receipt and disposal. The certification program should
9 describe the administrative process for attaining authorization from the disposal facility to
10 transfer the waste for disposal once the waste has been certified.

11
12 The procedures should require characterization of the waste, as well as inspection of the
13 characterization process to demonstrate that it meets the acceptance criteria. Guidance on
14 acceptable characterization is discussed in Section 9.2. For waste that does not meet the
15 acceptance criteria when inspected, the procedures should specify the administrative process
16 that a waste generator would need to follow to gain acceptance and properly certify that the
17 waste is acceptable for disposal.

18
19 The procedures should also document the necessary steps for complying with the applicable
20 transportation requirements for the transfer of certified waste to the land disposal facility,
21 including those specified by the Department of Transportation and in 10 CFR Part 71. These
22 requirements include the requirements for transfer of waste intended for disposal at a licensed
23 land disposal facility that are found in Appendix G to 10 CFR Part 20.

24
25 The procedures should clearly describe the process for maintaining the waste certification until
26 the waste has been placed in a disposal unit at the land disposal facility. Guidance on
27 procedures for maintaining certification is provided in Section 9.3.2. As part of certification
28 maintenance, the certification program should also identify adequate procedures for receipt and
29 inspection of waste at the disposal facility to ensure that arriving waste shipments are in
30 compliance with applicable Federal regulations and the waste acceptance criteria. Standard
31 Review Plan 4.1 of NUREG-1200 (NRC, 1994) provides guidance on developing adequate
32 procedures for receipt and inspection of waste arriving at a disposal facility. Standard Review
33 Plan 8.6 of NUREG-1200 (NRC, 1994) also discusses guidance on administrative and operating
34 procedures that may be applicable. The IAEA has also published guidance on inspection and
35 verification of waste packages for near-surface disposal that may be applicable to developing
36 adequate procedures (IAEA, 2000).

37
38 Finally, the procedures should clearly describe the process for restricting access to disposal for
39 waste generators that are not meeting the requirements of the certification program. The
40 procedures should identify conditions that would warrant restriction of generator access to
41 disposal including, for example: radiological contamination; wastefrom or container integrity
42 deficiencies; improper characterization; improper manifesting; transportation violations;
43 inadequate nuclear safety limits; and improper certification maintenance. These procedures
44 may include suspension of access to disposal capacity or possible heightened oversight by the
45 disposal facility operator and its regulatory authority, and should describe corrective actions
46 necessary to restore access to the disposal facility following suspension.

47

1 **9.3.1.3 Certification Documentation**
2

3 The key document in a waste certification is the certification statement. The certification
4 statement is the documentation signed by a designated official that certifies that the waste
5 meets the waste acceptance criteria of the disposal facility. The certification statement should
6 also include information required by the certification program, including radiological properties,
7 wasteform characteristics, and container specifications. Licensees should use the waste
8 acceptance criteria to identify key elements to include as part of the waste certification
9 statement. In addition to the certification statement, documentation should also include
10 confirmation that an official from the disposal facility to which the waste is to be transferred has
11 authorized transfer of the waste to the disposal facility.
12

13 The documentation supporting the waste certification statement may include or reference the
14 following information. The land disposal facility may use a graded approach to determine which
15 of the following information is necessary for generators to provide prior to granting authorization
16 to transfer waste to the disposal facility. A graded approach would focus on information that is
17 necessary for generators to provide that is significant for demonstrating the waste acceptance
18 criteria have been met and the waste can be certified as acceptable.
19

- 20 • **Waste Stream Profile.** The waste stream profile is a description of the waste stream,
21 generally identifying the source, physical and chemical description, and upper limits on
22 radionuclides.
23
- 24 • **Radionuclide Content.** Radionuclide content includes the concentration and inventory
25 of radionuclides determined from waste characterization. See Section 9.2 for guidance
26 on waste characterization.
27
- 28 • **Radiological Surveys.** Survey results include the determination of the surface
29 contamination of the waste container and the external dose rate if necessary for waste
30 certification.
31
- 32 • **Waste Container Attributes.** Container attributes include information about the
33 physical attributes (e.g., dimensions) of the container as well as any necessary
34 procurement information relevant to certification. Disposal facility operators may require
35 generators to provide container specifications, particularly if they are relied upon by the
36 land disposal facility operator for defense-in-depth. Each container specification should
37 include a description of the specification's purpose, procedures for complying with the
38 requirements of the specification, description of the container and manufacturing
39 specification, and results of tests to assess the integrity of the container.
40
- 41 • **Uniform Low-Level Radioactive Waste Manifest.** The manifest is required by
42 Appendix G to 10 CFR Part 20 for transfers of waste intended for disposal at licensed
43 land disposal facilities (NRC, 1998).
44
- 45 • **Quality Assurance Records.** QA records may include documentation of testing or
46 inspections required for waste certification, particularly for defense-in-depth protections.
47 The records may also include a statement ensuring access for designees of the land
48 disposal facility to perform audits and inspections. This may include assurance of

1 access to the providers of procured items or services that are significant to certify that
2 the waste acceptance criteria are met.

- 3
4 • **Certification Maintenance Procedures.** Certification maintenance procedures include
5 the processes and controls required to maintain waste certification. Guidance on
6 certification maintenance is provided in Section 9.3.2.

7
8 The waste certification program should also identify which records need to be maintained and
9 how they are to be maintained. The certification program may detail specific records
10 management requirements, or may simply invoke an existing acceptable records management
11 program such as one that complies with the requirements of 10 CFR 61.80.

12 **9.3.1.4 Audits of Certifications**

13
14 A certification program should also formalize procedures for independent audits of individuals or
15 organizations designated to certify waste as acceptable for disposal by the land disposal facility
16 operator. Standard Review Plan 8.5 of NUREG-1200 (NRC, 1994) provides guidance on plans
17 for conducting reviews and audits of operational activities important to safety that may also be
18 applicable to audits of the certification process. The periodic audits should provide an
19 independent verification of the implementation of the certification program. The audit
20 procedures should describe the principle documents of the waste certification record that will be
21 audited and the frequency of audits.

22
23 The principal documents that should be subject to inspection may include the waste certification
24 statement, procurement or purchasing documents (e.g., for approved containers), radiological
25 survey data, and laboratory testing data for characterization required to demonstrate
26 conformance with the waste acceptance criteria. Audits may also include observation of testing
27 and characterization that are significant to demonstrating the waste acceptance criteria are met
28 as well as how the certification process is implemented by the certifying organization.
29 Licensees may use a graded approach to determine the documents subject to audit and the
30 frequency of the audits for a given certifying organization. The certification program should
31 identify the records required to adequately document the audits and the management
32 requirements for the audit records. Licensees should maintain records of the certification audits
33 for inspection by the NRC.

34 **9.3.2 Certification Maintenance**

35
36 Waste that has been certified as meeting the waste acceptance criteria for a land disposal
37 facility must be controlled so that the certification remains valid until disposal at the facility.
38 Otherwise, the waste will need to be re-certified. The waste certification program should identify
39 the requirements for protecting the certification status of the waste. These requirements may be
40 specific to a waste stream or applicable to all waste streams. The certifying organization should
41 develop procedures for maintaining the waste certification that comply with the certification
42 program's requirements. Certification maintenance may be especially important for waste that
43 will be stored for long periods of time or significantly treated or conditioned prior to disposal.

44
45 Requirements for maintaining the certification status include protecting the waste container,
46 preventing unauthorized introduction of material into the waste, protecting the data marked on
47 the waste container, and protecting any other capabilities relied upon for defense-in-depth.

1 Requirements for protection of the waste container may include sufficient protection from the
2 environmental conditions during storage, conditioning, or transport (e.g., precipitation, heat, ultra
3 violet) or designated limits for damage, should it occur. Waste may also need to be controlled in
4 a manner that prevents modifying the contents. These controls may include requirements for
5 tamper indication devices and secured storage depending on the waste stream. It is also
6 important to be able to relate each container to information about the certification of the
7 container. Therefore, licensees may need to have requirements regarding container markings
8 to protect from defacement or removal. Also, licensees should safely store records regarding
9 certification.

10 **9.4 Periodic Review**

11
12 The regulations at 10 CFR 61.58(f) require disposal facility licensees to review the content and
13 implementation of their waste acceptance program at least annually. The purpose of this review
14 is to ensure that the content of the waste acceptance program continues to be adequate and
15 that the program is being implemented in a way that continues to protect public health and
16 safety. As part of this annual review of the waste acceptance program, disposal facility
17 licensees should also evaluate and document whether waste acceptance criteria continue to be
18 protective of public health and safety. If the evaluation indicates that the waste acceptance
19 criteria continue to provide reasonable assurance that the performance objectives will be met
20 and adequate defense-in-depth will be maintained, the documentation should include the basis
21 for relying on the existing waste acceptance criteria. If the evaluation finds that the waste
22 acceptance criteria no longer provide reasonable assurance that the performance objectives will
23 be met or that defense-in-depth protections are inadequate, the criteria should be updated. The
24 licensee should submit the amended criteria and supporting technical analyses that
25 demonstrate the performance objectives will be met as part of a request for amendment to the
26 license.

27
28 Periodic reviews should incorporate the following features to assess procedural compliance,
29 technical performance, implementation, and effectiveness of the facility waste acceptance
30 program:

- 31
32 • **Waste acceptance supervisory reviews.** Onsite waste acceptance supervisors should
33 periodically perform and document reviews of the effectiveness of the waste acceptance
34 personnel in such areas as development of waste acceptance criteria, characterization
35 adequacy, and procedural compliance.
- 36
37 • **Quality assurance audits.** Quality assurance audits should be performed by the onsite
38 auditing group. Personnel in the auditing group should have sufficient waste acceptance
39 training or experience so they can determine whether waste acceptance functions (e.g.,
40 characterization or certification) are being performed as required. These audits should
41 also be performed periodically at generators.
- 42
43 • **Corporate or contract audits.** Offsite (corporate or contract) audits and evaluations
44 should be performed to determine whether the waste acceptance program complies with
45 the regulations and other requirements and whether objectives are being met as well as
46 to identify needed program improvements.

47

1 Periodic review records should contain the following information to be acceptable: date of the
2 review, name of person(s) who conducted the review, persons contacted by the reviewer(s),
3 areas reviewed, review findings, corrective actions, and follow-up. The licensee is not required
4 to submit documentation of its periodic review to the NRC. Rather, licensees should maintain
5 the records as required in 10 CFR 61.80. However, if a licensee identifies during its periodic
6 review a significant implication for public health and safety or common defense and security, the
7 licensee shall notify the NRC as required by 10 CFR 61.9a(b).

8 **9.5 Mitigation**

9
10 In some cases, a land disposal facility may learn of new information that indicates that
11 previously disposed of waste may present an unreasonable risk to public health and safety or
12 the environment. For example, the new information may indicate a significant reduction in the
13 expected performance of engineered or intruder barriers or the site characteristics to limit
14 radionuclide release and migration. In these cases, licensees may need to consider mitigation
15 to reduce the impact to humans or the environment to ensure that waste disposal continues to
16 meet the performance objectives with reasonable assurance and provides defense-in-depth
17 protections. Mitigation could take many different forms, such as but not limited to, modification
18 of the disposal facility design or remediation of the disposed waste. This section of the
19 guidance document describes when licensees should consider mitigation, what information they
20 should provide to the regulator to demonstrate that mitigation has been implemented, and what
21 a reviewer should evaluate to verify that mitigation has occurred.

22
23 As licensees periodically update the waste acceptance criteria, new information may be learned
24 that, when considered in the technical analyses, could indicate that waste previously accepted
25 for disposal may present an unreasonable risk to public health and safety or the environment.
26 Additionally, prior to final closure of the disposal site, the licensee, per the requirements of
27 10 CFR 61.28, shall submit an application to amend the license for closure upon which the
28 Commission shall make a determination if there is reasonable assurance that the performance
29 objectives of 10 CFR Part 61 will be met and that defense-in-depth protections have been
30 provided. A component of the application for closure should include a final set of technical
31 analyses and a final revision of the safety case to demonstrate that the performance objectives
32 will continue to be met after closure. If a land disposal facility determines during updates to the
33 waste acceptance criteria or the closure process that the facility is no longer meeting the
34 performance objectives, mitigation is one method of bringing the facility into compliance.

35
36 Before engaging in mitigation, a licensee should provide information describing the actions they
37 propose to take, including the basis for those actions. The proposed actions could include
38 modification of the disposal facility design or remediation. Design modifications could include
39 installation of a higher performance engineered cover or the use of permeable treatment walls,
40 diversion ditches, sheet piling, and so forth. The licensee's design modifications should be
41 developed through consideration of the results of the technical analyses. Remediation of the
42 disposed waste may involve actions such as *in situ* stabilization of the wasteforms (e.g.,
43 grouting) and removal of a portion of or the entire unacceptable waste inventory for offsite
44 disposal. The licensee should provide a technical basis that demonstrates 10 CFR 61.43 (i.e.,
45 protection of individuals during operations) will be met during remediation. They should develop
46 a cost-benefit analysis to inform the selection of remedial actions.

1 A reviewer should evaluate the information provided by the licensee, including the technical
2 basis for the proposed actions. The reviewer should evaluate the alternatives considered and
3 the basis for the action selected. If design modifications are proposed, the reviewer should
4 evaluate the technical basis for the performance of engineered barriers. The reviewer should
5 determine if the licensee's desired performance of the engineered barriers is likely to be
6 achieved. The reviewer should determine if the design modifications were developed in
7 consultation with the results of the technical analyses. If remediation is selected, the reviewer
8 should evaluate the basis for how much waste the licensee would remove and how the licensee
9 would remove the waste. The technical basis demonstrating that 10 CFR 61.43 will be met
10 should be reviewed. Finally, the reviewer should evaluate cost-benefit analyses that have been
11 developed to ensure the mitigation activities are justified.
12
13

10.0 PERFORMANCE CONFIRMATION

Performance confirmation is the program of tests, experiments, and analyses that licensees conduct to evaluate and verify the accuracy of information used to demonstrate that the 10 CFR Part 61 performance objectives are met before disposal site closure. Prior to final closure of the disposal site, licensees are required by 10 CF 61.28 to submit an application to amend the license for closure. The closure application must include the specific details of the site closure plan. The plan must include additional geologic, hydrologic, and other disposal site data pertinent to the long-term containment of emplaced radioactive wastes obtained during the operational period. In addition, the plan must include the results of tests, experiments, or other analyses pertinent to the long-term containment of emplaced waste within the disposal site. Licensees must update the technical analyses for 10 CFR 61.13 using details of the final closure plan and the waste inventory. Although the terminology “performance confirmation” is not used in the regulation, as discussed below, the NRC staff believes that the elements of a performance confirmation program are supported by 10 CFR Part 61. Elements of performance confirmation may be completed during active operation as well as during the institutional control period. The following are the main elements of a performance confirmation program:

- verification that site conditions encountered during construction were within limits assumed during licensing
- verification that engineered barriers and other defense-in-depth protections were constructed as designed and will perform within limits assumed during licensing
- verification of the performance of natural barriers that were relied upon by the licensee in licensing to achieve compliance with the performance objectives
- monitoring of facility performance
- verification of the safety case

Performance confirmation is integrated with disposal system design, development, and construction to provide confidence that the disposal system will perform as intended. Performance confirmation can be used to supplement information satisfying the requirements of 10 CFR 61.28, 10 CFR 61.52, and 10 CFR 61.53.

The NRC staff expects that licensees may obtain additional geologic, hydrologic, or other disposal site data pertinent to the long-term containment of emplaced radioactive wastes during the operational period. In addition, monitoring of the performance of the disposal facility and minor custodial care is required for the duration of the institutional control period. Additional data with respect to facility performance and site conditions may be obtained during the institutional control period. Under 10 CFR 61.28 licensees are required to update technical analyses; the Commission will issue an amendment authorizing closure if the updated analyses demonstrate that the 10 CFR Part 61 performance objectives are met (e.g., performance assessment, intruder assessment, site stability evaluation, defense-in-depth analyses, protective assurance period analyses, and performance period analyses). A performance confirmation program can be used to proactively generate information to support updating the technical analyses for closure. The performance confirmation program can be designed to produce information to support the most risk-significant and uncertain elements of the technical analyses.

1 **Table 10-1 Regulatory Requirements Supportive of Performance Confirmation**

Section	Requirement
10 CFR 61.7(c)(3)	Post-closure monitoring and maintenance
10 CFR 61.12(g)	A description of the disposal site closure plan, including those features that facilitate closure and eliminate the need for maintenance
10 CFR 61.28	Contents of application for closure
10 CFR 61.52	Land disposal facility operation and disposal site closure
10 CFR 61.53(c)	Environmental monitoring during construction and operation
10 CFR 61.53(d)	Environmental monitoring, post operational surveillance

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It is good practice for a licensee to update the technical analyses supporting licensing (e.g., performance assessment and intruder assessment) at regular intervals. Upon amending waste acceptance criteria to accept new waste, proposing changes to the design of the disposal site, or when new information about site characteristics or design properties becomes available, the licensee should determine if the site will continue to comply with the Subpart C performance objectives and, if necessary, update the analyses. While a regular interval for updating the technical analyses is not specified in the regulation, 10 CFR 61.58(f) requires licensees to annually review the content and implementation of their waste acceptance program. The purpose of this review, as described further in Section 9.4 of this document, is to ensure that the content of the waste acceptance program continues to be adequate and that the program is being implemented in a way that continues to protect public health and safety. As part of this annual review, licensees should also evaluate and document whether the waste acceptance criteria continues to provide reasonable assurance of compliance with the Subpart C performance objectives. If the evaluation finds that the waste acceptance criteria do not provide reasonable assurance of compliance with the Subpart C performance objectives, the licensee should submit the revised criteria and supporting technical analyses that demonstrate that the proposed criteria meet the performance objectives as part of a request for amendment to the license.

1 Updating technical analyses can ensure that appropriate operational practices (e.g., allowable
2 limits) are identified and implemented to reduce the potential need for more challenging
3 mitigation activities (e.g., installing new barriers, removing waste). Conditions that could trigger
4 a decision to update waste acceptance criteria, and therefore to update technical analyses, may
5 include but are not limited to the following:
6

- 7 (1) substantially different inventory than anticipated (e.g., quantity, concentration, form)
- 8 (2) new site information (e.g., environmental conditions, characterization data)
- 9 (3) new information on engineered barrier performance or other defense-in-depth
10 protections
- 11 (4) monitoring data that are inconsistent with current analyses
- 12 (5) substantial changes to relevant scientific understanding
- 13 (6) use of updated dosimetry

14
15 Licensees should document the basis for their decision on whether the waste acceptance
16 criteria and supporting technical analyses should be updated. The availability of new
17 information may not always prompt a decision to update the waste acceptance criteria and
18 supporting technical analyses. The operating period of a disposal facility may extend over
19 multiple decades, and the NRC staff expects that new information will be developed. Regular
20 updating is advised because it will allow a licensee to evaluate relevant information generated
21 since the previous update. Regular updating will also reduce the likelihood that something
22 unforeseen develops that calls into question the performance of the disposal facility. In some
23 cases, significant information may become available to a licensee. The licensee should
24 determine, in consultation with the pertinent regulator, if the new information warrants an update
25 to the technical analyses.
26

27 Monitoring of environmental media is required by 10 CFR 61.53. Monitoring is required to
28 provide early warning of release of radionuclides from the disposal site before they leave the
29 site boundary. Most monitoring systems focus on sampling environmental media, such as
30 groundwater or the atmosphere, some distance from the facility, such as within the buffer zone
31 surrounding the facility or at the site boundary. It may be useful for a licensee to identify and
32 use performance indicators. A performance indicator is a measure of the performance of
33 subsystems of the disposal system that may be a precursor to the overall performance of the
34 disposal system. Performance indicators may be a less direct measure of overall performance
35 but have the advantage of providing early warning of changes in system performance. For
36 example, monitoring of soil moisture underneath an engineered cover may provide an indication
37 of increased infiltration that may lead to increased release of radioactivity from the disposal
38 facility.
39

40 Licensees can use technical analyses supporting demonstration of compliance with the
41 performance objectives to help determine what types of information would be most useful to
42 monitor and when that information is significant. Monitoring data typically have moderate to
43 significant variability. If monitoring data are used in performance confirmation, the NRC staff
44 recommends that a licensee provide a description of the anticipated variability of monitoring
45 data to help prevent misinterpretation of observational data. In some cases, a monitoring
46 observation may appear to be an outlier. Licensees should not reject data as outliers without a
47 statistical or physical basis. If a statistical basis cannot be provided, additional information
48 should be collected. Reviewers should evaluate the technical basis for the treatment of outliers
49 and determine if it is adequate. In some cases, a technical explanation may be available (e.g.,

1 the sample was contaminated). It is possible that initial information may appear to represent an
2 outlier, however, in reality the observed behavior is not due to measurement error, for example,
3 but rather represents complex, unanticipated phenomena. Licensees should use caution in
4 dismissing outliers in observational data.

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11.0 USE OF OTHER NRC GUIDANCE DOCUMENTS

The following tables are intended to provide references that may be useful to licensees in developing their technical analyses. Tables 11-1, 11-2, and 11-3 present references according to the performance objectives in 10 CFR Part 61. Table 11-4 provides a list of general topics and associated references. NUREG-1573 includes a bibliography of technical references applicable to LLW disposal (as of 2000) in its Appendices B and C (NRC, 2000a) that may also be useful to licensees and reviewers.

Table 11-1 Guidance Crosswalk for Performance Objective 10 CFR 61.41, Performance Assessment

Document	Description
NUREG-1573, "A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities" (NRC, 2000a)	Section 2, regulatory framework for 10 CFR Part 61
	Section 3.1, performance assessment approach
NUREG-1200, "Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility" (NRC, 1994)	Review procedures for technical analysis
NUREG-1757, "Consolidated Decommissioning Guidance" (NRC, 2006)	Volume 2, Section 3.5, evaluation of engineered barriers
NUREG/CR-5512, "Residual Radioactive Contamination from Decommissioning" (NRC, 1992)	Volume 1, Appendix E, Table E.6, solubility classes
NUREG-1854, "NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations" (NRC, 2007a)	Section 4.2, guidance on review of performance assessments for waste determinations, general technical review procedures

Table 11-2 Guidance Crosswalk for Performance Objective 10 CFR 61.42, Inadvertent Intruder Assessment

Document	Description
NUREG-1854, "NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations" (NRC, 2007a) ¹	Guidance on review of intruder analyses for waste determinations
NUREG-0782, "Draft Environmental Impact Statement on 10 CFR Part 61 Licensing Requirements for Land Disposal of Radioactive Waste" (NRC, 1981a)	Describes the intruder assessment methodology used to develop waste classification tables in 10 CFR 61.55, including generic scenarios
NUREG-0945 "Final Environmental Impact Statement on 10 CFR Part 61 Licensing Requirements for Land Disposal of Radioactive Waste" (NRC, 1982b)	Acceptable methods of concentration averaging
NUREG/CR-1759, "Data Base for Radioactive Waste Management" (directly supports NUREG-0782) (NRC, 1981b)	Guidance on classifying waste Various methods to determine radionuclide concentrations
Revised Draft Branch Technical Position on Concentration Averaging and Encapsulation, Rev. 1, May 2012 (NRC, 2012a)	Guidance on wasteforms to comply with waste characteristics requirements in 10 CFR 61.56
"Final Waste Classification and Waste Form Technical Position Papers," Rev. 0, May 11, 1983 (NRC, 1983d)	Section 3.3, model abstractions for a performance assessment, generally applicable to intruder assessment
"Technical Position on Waste Form (Revision 1)", January 18, 1991 (NRC, 1991b)	
NUREG-1573, "A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities" (NRC, 2000a)	

¹ Many of these references also apply to performance objective 10 CFR 61.41.

Table 11-2 Guidance Crosswalk for Performance Objective 10 CFR 61.42, Inadvertent Intruder Assessment

Document	Description
<p>NUREG-1200, "Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility" (NRC, 1994)</p>	<p>Section 6.1, evaluation of pathways in total dose calculation</p> <p>Volume 2, Section 3.5.4, degradation mechanisms, capabilities of engineered barriers</p> <p>Volume 2, Section 3.5.5, summary of existing guidance and reference information for application of engineered barriers at disposal facilities</p>
<p>NUREG-1757, "Consolidated Decommissioning Guidance" (NRC, 2006)</p>	<p>Appendix M, Table M.5-M.12, water quality standards</p> <p>Appendix M.5, Potential sources of land use information</p>
<p>NUREG/CR-4370, "Update of Part 61 Impacts Analysis Methodology" (NRC, 1986a)</p>	<p>Section I.6, selecting site-specific input parameters for models and providing a technical basis</p> <p>Section I.5, selection of codes/models and approaches for NRC acceptance of the codes/models</p> <p>Provides scenarios and calculation approach to estimate intruder doses</p>

Table 11-3 Guidance Crosswalk for Performance Objective 10 CFR 61.44, Site Stability Analysis

Document	Description
NUREG-1623, "Design of Erosion Protection for Long-Term Stabilization" (NRC, 2002b)	Design of erosion protection at uranium mill tailings sites Procedure for determining the suitability of a rock source
NUREG-1804, "Yucca Mountain Review Plan" (NRC, 2003c)	Seismic events in waste disposal
NUREG-1200, "Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility" (NRC, 1994)	Site stability analysis for long-lived waste
NUREG-1757, "Consolidated Decommissioning Guidance" (NRC, 2006)	Section 3.5, risk-informed approach to engineered barriers
	Analog for wasteform stability
	Durability of earthen covers
	Section 3.5.5, reference information regarding engineered cover design and performance
NUREG/CR-2642, "Long-Term Survivability of Riprap for Armoring Uranium Mill Tailings and Covers" (NRC, 1982c)	Appendix P, evaluations of rock durability
	Table 6.7, comparative data on natural materials
	Appendix A, information on rock weathering, durability, examples of analogs
Technical Position on Waste Form (Revision 1) (NRC, 1991b)	Specific test procedures and criteria to evaluate wasteform stability
NUREG-0902, "Site Suitability, Selection and Characterization, BTP – Low-Level Waste Branch" (NRC, 1982e)	Provides additional information on processes to be avoided that may affect site stability

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
Analysis Timeframe	<p>NUREG-1573, "A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities" (NRC, 2000a)</p> <p>"Technical Analysis Supporting Definition of Period of Performance for Low-Level Waste Disposal" (NRC, 2011c)</p>
Radon Diffusion and Barriers	<p>Regulatory Guide 3.64, "Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers" (NRC, 1989a)</p> <p>NUREG/CR-4370, "Update of Part 61 Impacts Analysis Methodology" (NRC, 1986a)</p>
Sensitivity/Uncertainty Analysis	<p>NUREG-1757, "Consolidated Decommissioning Guidance," Vol. 2, Appendix I, Section 1.7 (NRC, 2006)</p> <p>NUREG-1573, Section 3.3.2 (NRC, 2000a)</p>
Expert Elicitation and Judgment	<p>NUREG-1563, "Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program" (NRC, 1996)</p>
Modelling Climate and Infiltration	<p>NUREG-1573, Section 3.3.3 (NRC, 2000a)</p> <p>NUREG-1854, Section 4.3.1 (NRC, 2007a)</p>

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
Waste Acceptance Criteria	<p>Revised Draft Branch Technical Position on Concentration Averaging and Encapsulation, Rev. 1, May 2012 (NRC, 2012a)</p> <p>Final Waste Classification and Waste Form Technical Position Papers,” Rev. 0, May 11, 1983 (NRC, 1983d)</p> <p>Technical Position on Waste Form, Rev. 1 (NRC, 1991b)</p> <p>NUREG-1200, SRP 4.1, SRP 6.11 (NRC, 1994)</p>
Waste Characterization	<p>See Waste Acceptance Criteria (NRC, 1983d); (NRC, 2012a); (NRC, 1991b)</p> <p>NUREG/CR-6567, “Low-Level Radioactive Waste Classification, Characterization, and Assessment: Waste Streams and Neutron-Activated Metals.” (NRC, 2000b)</p> <p>NUREG-1575, “Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME),” Supplement 1 (NRC, 2009)</p> <p>NUREG-1576, “Multi-Agency Radiological Laboratory Analytical Protocols Manual (MARLAP)” (NRC, 2004b)</p> <p>NUREG-1200, SRP 8.6, SRP 9.1 (NRC, 1994)</p>

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
Waste Certification	<p>NUREG-1200, SRP 8.5 (NRC, 1994)</p> <p>NUREG/BR-0204, "Instructions for Completing NRC's Uniform Low-Level Radioactive Waste Manifest", Revision 2, July 1998 (NRC, 1998)</p>
Source Term Modelling	<p>NUREG-1573, Section 3.3.5 (NRC, 2000a)</p> <p>NUREG-1854, Section 4.3.3 (NRC, 2007a)</p>
Inventory Abstraction	<p>NUREG-1573, Sections 3.3.5.1, 3.3.5.2, and 3.3.5.7 (NRC, 2000a)</p> <p>NUREG-1854, Sections 3.1 and 4.3.3.1.1 (NRC, 2007a)</p>
Chemical Environment and Abstraction	<p>NUREG-1573, Section 3.3.5.6 (NRC, 2000a)</p> <p>NUREG-1854, Section 4.3.3.1.4 (NRC, 2007a)</p> <p>NUREG-1804, "Yucca Mountain Review Plan," Section 4.2.1.3.3 (NRC, 2003c)</p>
Waste Containers, Wasteform, and Waste Type	<p>NUREG-1573, Section 3.3.5.4 (NRC, 2000a)</p>
Wasteforms and Degradation	<p>NUREG-1854, Section 4.3.3.1.2 (NRC, 2007a)</p>
Engineered Barriers	<p>NUREG-1573, Section 3.3.4 (NRC, 2000a)</p> <p>NUREG-1854, Section 4.3.2 (NRC, 2007a)</p> <p>NUREG-1804, Sections 4.2.1.3.1 and 4.2.1.3.2 (NRC,</p>

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
	2003c)
Aqueous Release Models	NUREG-1854, Section 4.3.3.2 (NRC, 2007a)
Gaseous Release Screening, Processes Generating Gases	NUREG-1804, Section 4.3.1.2.4 (NRC, 2003c)
Climate and Infiltration Modelling	NUREG-1573, Sections 3.3.5.7.1 and 3.3.5.7.2 (NRC, 2000a)
	NUREG-1573, Section 3.3.3 (NRC, 2000a)
	NUREG-1854, Section 4.3.1(NRC, 2007a)
Biosphere Characteristics and Dose Modelling	NUREG-1573, Section 3.3.7 (NRC, 2000a)
	NUREG-1854, Section 4.3.5 (NRC, 2007a)
Transport Modelling	NUREG-1573, Section 3.3.6 (NRC, 2000a)
	NUREG-1854, Section 4.3.4 (NRC, 2007a)
Groundwater Transport	NUREG-1573, Section 3.3.6.1.2 (NRC, 2000a)
Surface Water Transport	NUREG-1573, Section 3.3.6.2 (NRC, 2000a)
Atmospheric Transport	NUREG-1854, Section 4.3.4.1.2 (NRC, 2007a)
	NUREG-1573, Sections 3.3.6.3.2.1 and 3.3.6.3.2 (NRC, 2000a)

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
Development of a License Application for an LLW Disposal Facility	<p>NUREG-1199, "Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility," Revision 2 (NRC, 1991a)</p> <p>Regulatory Guide 4.18, "Standard Format and Content of Environmental Reports for Near-Surface Disposal of Radioactive Waste" (NRC, 1983e).</p> <p>NUREG-1300, "Environmental Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility" (NRC, 1987)</p>
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	<p>NUREG-0902, "Site Suitability, Selection and Characterization, BTP – Low-Level Waste Branch" (NRC, 1982e)</p> <p>Regulatory Guide, 4.19, "Guidance for Selecting Sites for Near-Surface Disposal of Low-Level Radioactive Waste" (NRC, 1988b)</p>
Scenario Development	NUREG/CR-5927, Vol. 1, (SAND91-2802), "Evaluation of a Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities: Evaluation of Modeling Approaches," (NRC, 1993a)

Table 11-4 Guidance Crosswalk by Topic

Topic	Document
	<p>NUREG-1200, Section 2.4.1, Appendix A (NRC, 1994)</p> <p>NUREG-1199, "Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility," Revision 2 (NRC, 1991a)</p> <p>NUREG-1623, "Design of Erosion Protection for Long-Term Stabilization," (NRC, 2002b)</p>

12.0 REFERENCES

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13.0 GLOSSARY

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

Alternative scenario: In addition to the central scenario, possible future evolution of the disposal site. Alternative scenarios may include disruptive events if those FEPs are relevant at a particular site.

Analysis timeframe: The timeframe over which a licensee should assess the projected performance of the disposal facility factoring in the characteristics of the waste, engineered barriers, disposal site, and associated uncertainties. The analysis timeframe is divided into two phases: a compliance period and a performance period.

Assessment Context: The assessment context provides a framework for performance assessment and covers the following key aspects: purpose; regulatory framework; assessment end-points; assessment philosophy; disposal system (or facility) characteristics; and timeframes.

Buffer zone: Portion of the disposal site that is controlled by the licensee and that lays under the disposal units and between the disposal units and the boundary of the site.

Central scenario: The scenario that the licensee can best support as to the expected future dynamic evolution of the disposal site. As a result of the site selection process for low-level waste disposal, the central scenario generally will not include disruptive events.

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

Compliance period: The period of time over which a licensee must demonstrate with reasonable assurance that the disposal facility will meet the performance objectives found in 10 CFR 61.41(a), 10 CFR 61.42(a), and 10 CFR 61.44. A quantitative assessment should be performed. The compliance period is defined by 10 CFR 61.2 to be the time out to 1,000 years after closure of the disposal facility.

Computational model: See *Numerical model*.

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

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

1
2 **Defense-in-depth:** The use of multiple independent and redundant layers of defense such that
3 no single layer, no matter how robust, is exclusively relied upon. Defense-in-depth for a land
4 disposal facility includes, but is not limited to, the use of siting, waste forms and radionuclide
5 content, engineered features, and natural geologic features of the disposal site.
6
7 **Degradation:** A process of gradual reduction in the capability of materials used in the
8 construction of low-level waste disposal facilities to limit water infiltration and the release of
9 radionuclides; the decline of an engineered barrier following the service life, when important
10 characteristics of an engineered barrier progress from an expected design value to the
11 degraded condition.
12
13 **Degraded barrier:** An engineered barrier that has fully undergone the process of degradation
14 resulting in reduced material and performance characteristics: a degraded barrier could still
15 perform a function based on the properties of the remaining durable constituent materials.
16
17 **Deterministic analysis:** An analysis using a single set of values for key assumptions or
18 parameters to calculate a single value of model output.
19
20 **Disposal:** Placement of waste in a facility designed to isolate waste from the accessible
21 environment without an intention to retrieve the waste.
22
23 **Disposal site:** That portion of a land disposal facility which is used for disposal of waste. It
24 consists of disposal units and a buffer zone.
25
26 **Disposal unit:** A discrete portion of the disposal site into which waste is placed for disposal.
27 For near-surface disposal the unit is usually a trench.
28
29 **Distribution coefficient (K_d):** An empirical constant employed in mathematical expressions
30 representing sorption isotherms that relate the mass of solute on the solid phase to the
31 concentration of solute in solution as a function of temperature and pressure. The distribution
32 coefficient (K_d) represents an empirical constant for a linear sorption isotherm, the validity of
33 which requires that the reactions that cause the partitioning are fast and reversible (e.g.,
34 chemical equilibrium is achieved) and the sorption isotherm is linear.
35
36 **Dose:** Generically refers to radiation dose, absorbed dose, dose equivalent, effective dose
37 equivalent, committed dose equivalent, committed effective dose equivalent, or total effective
38 dose equivalent.
39
40 **Dosimetry:** The process or method of measuring the dosage of ionizing radiation.
41
42 **Engineered barrier:** A man-made feature that is intended to improve the land disposal facility's
43 ability to meet the performance objectives in Subpart C. Examples of engineered barriers
44 include intruder barrier, resistive cover, evapotranspiration or water balance cover, and clay
45 cap.
46
47 **Exposure pathway:** The route by which radioactivity travels through the environment to
48 produce radiation exposure to a person or group.
49

1 **Exposure scenario:** See *Receptor scenario*.
2
3 **Event:** A qualitative or quantitative phenomenon or change that has the potential to affect the
4 performance of the disposal system and that occurs during an interval that is short compared to
5 the analyses timeframe. Examples of events that cause relative rapid change are earthquakes,
6 floods, storms, well drilling, and excavation.
7
8 **Feature:** An object, structure, or characteristic that has a potential to affect the performance of
9 the disposal system. Examples include rocks within an erosion layer of an engineered cover or
10 a drainage layer of an engineered cover.
11
12 **FEP:** Feature, event, or process that has a potential to affect the performance of the disposal
13 system.
14
15 **FEP categorization:** The process of organizing individual FEPs into categories of similar
16 properties to facilitate FEP screening. For example, FEPs related to natural, human, or waste
17 phenomena may be grouped into separate categories.
18
19 **FEP screening:** The process of using regulatory, probability, and consequence criteria to
20 eliminate FEPs from further consideration that will not significantly impact the performance of
21 the disposal system or are otherwise excluded by regulation.
22
23 **Hazard:** A feature, event, or process that is capable of causing harm. In waste disposal, the
24 radiological inventory represents a hazard but if contained does not present risk to the public.
25
26 **Inadvertent intruder:** Any person who might occupy the disposal site after closure and engage
27 in normal activities, such as agriculture, dwelling construction, resource exploration or
28 exploitation (e.g., well drilling) or other reasonably foreseeable pursuits that might unknowingly
29 expose the person to radiation from the waste.
30
31 **Institutional controls:** Measures to control access to a site and minimize disturbances to
32 engineered measures established by the licensee to control the residual radioactivity.
33 Institutional controls include administrative mechanisms (e.g., land use restrictions) and may
34 include, but are not limited to, physical controls (e.g., signs, markers, landscaping, and fences).
35
36 **Intruder assessment:** An analysis that (1) assumes an inadvertent intruder occupies the site
37 or contacts the waste and engages in normal activities or other reasonably foreseeable pursuits
38 that might unknowingly expose the person to radiation from the waste; (2) examines the
39 capabilities of intruder barriers to inhibit an inadvertent intruder's contact with the waste or to
40 limit the inadvertent intruder's exposure to radiation; and (3) estimates an inadvertent intruder's
41 potential annual dose, considering associated uncertainties. Intruder assessments are
42 generally constrained to a limited set of receptor scenarios to avoid excessive speculation about
43 future human behavior. An intruder assessment is used to demonstrate compliance with
44 10 CFR 61.42(a) and 10 CFR 61.42(b).
45
46 **Intruder scenario:** See *Receptor scenario*.
47
48 **Land disposal facility:** The land, building, and structures, and equipment which are intended
49 to be used for the disposal of radioactive wastes.

1
2 **Licensee:** A person possessing a license to dispose of waste in a land disposal facility. In this
3 document the term “licensee” is meant to include both persons possessing a 10 CFR Part 61
4 license as well as applicants who are applying to obtain a 10 CFR Part 61 license.
5

6 **Long-lived waste:** Waste containing radionuclides (1) where more than 10 percent of the initial
7 activity of a radionuclide remains after 10,000 years (e.g., long-lived parent), (2) where the peak
8 activity from progeny occurs after 10,000 years (e.g., long-lived parent – short-lived progeny), or
9 (3) where more than 10 percent of the peak activity of a radionuclide (including progeny) within
10 10,000 years remains after 10,000 years (e.g., short-lived parent – long-lived progeny).
11

12 **Low-level (radioactive) waste (LLW):** Items that have become contaminated with radioactive
13 material or have become radioactive through exposure to radiation. The radioactivity in these
14 wastes can range from just above natural background levels to much higher levels, such as
15 seen in parts from inside the reactor vessel in a nuclear power plant. Low-level radioactive
16 waste is defined by what it is not, so that an understanding of the definitions of high-level
17 radioactive waste, spent nuclear fuel, transuranic waste, byproduct material, and naturally
18 occurring radioactive material is necessary to determine whether a subject waste is low-level
19 waste.
20

21 **Mathematical model:** A representation of a conceptual model in mathematical terms (i.e., a
22 governing equation or set of equations intended to represent important processes).
23 Mathematical models can be solved analytically or numerically.
24

25 **Member of the public:** An individual in a controlled or unrestricted area. However, an
26 individual is not a member of the public during any period in which the individual receives an
27 occupational dose.
28

29 **Model:** A conceptual or mathematical representation of a system used to project future
30 performance.
31

32 **Model abstraction:** The process of abstracting a conceptual model representing a dynamic
33 site in the physical world into a mathematical model governed by equations that is implemented
34 within a numerical model.
35

36 **Model integration:** The connection of models, submodels, and abstractions at the level of
37 detail necessary to represent the conceptual model. For example, a model simulating
38 precipitation may be integrated with models of infiltration and erosion.
39

40 **Model simplification:** The process of simplifying a complex numerical model into a reduced
41 numerical model while still maintaining the validity of the simulation results.
42

43 **Model support:** The technical basis that demonstrates the validity and appropriateness of the
44 results of the numerical model, and by extension provides support for the conceptual model.
45 The basis may include comparisons made with outputs of models (e.g., detailed process-level
46 models) and/or empirical observations (e.g., laboratory testing, field investigations, and natural
47 analogs).
48

1 **Model uncertainty:** The uncertainty in the conceptualization of the system, the uncertainty in
2 its mathematical representation, and the uncertainty in the solution of the mathematical
3 representation.
4

5 **Monitoring:** Observing and making measurements to provide data to evaluate the performance
6 and characteristics of the disposal site.
7

8 **Near-surface disposal facility:** A land disposal facility in which radioactive waste is disposed
9 of in or within the upper 30 meters of the earth's surface.
10

11 **Numerical model:** A model to solve the equations of the mathematical model using codes or
12 modeling software. The results of the simulations can represent, for example, potential
13 radiological exposures and their associated uncertainties.
14

15 **Parameter uncertainty:** Uncertainty associated with the input to the numerical model being
16 used in the analysis including uncertainty in the actual values and the statistical and spatial
17 distributions of data use to infer model parameters. Parameter uncertainty is highly dependent
18 on the quality of the data.
19

20 **Pathway:** Route or means of release of contaminants from a disposal facility, transport of
21 contaminants in the environment, or exposure of humans.
22

23 **Performance assessment:** An analysis that (1) identifies the features, events, and processes
24 that might affect the disposal system; (2) examines the effects of these features, events, and
25 processes on the performance of the disposal system; and (3) estimates the annual dose to any
26 member of the public caused by all significant features, events, and processes. A performance
27 assessment is used to demonstrate compliance with 10 CFR 61.41(a) and 10 CFR 61.41(b).
28

29 **Performance period:** The period of time over which a licensee evaluates the ability of the
30 disposal system to contain long-lived waste and demonstrates that releases are minimized to
31 the extent reasonably achievable. The performance period begins at the end of the protective
32 assurance period and extends as long as necessary to demonstrate that the metric of the
33 performance period can be met.
34

35 **Performance period analyses:** Analyses for certain types of waste for the timeframe after the
36 compliance period, which assess how the disposal facility and site characteristics minimize the
37 potential long-term impacts. Performance period analyses are required if the disposal facility is
38 accepting long-lived waste that has disposal site-averaged concentrations of long-lived
39 radionuclides greater than the values provided in Table A of 10 CFR 61.13(e). Performance
40 period analyses may be conservative screening analyses or a probabilistic risk assessment.
41

42 **Phenomenon:** Either a process or an event. Typically, a phenomenon acts upon a feature.
43

44 **Probabilistic analysis:** Refers to computer codes or analyses that use a sampling method to
45 select parameter values from a distribution. Results of the calculations are also in the form of a
46 distribution of values or time series of different values.
47

48 **Process:** A qualitative or quantitative phenomenon or change that has the potential to affect the
49 performance of the disposal system and that occurs during all or a significant part of the

1 analyses timeframe. Examples of processes that cause relative gradual change are
2 radionuclide transport, differential settlement, leaching, and erosion.

3
4 **Protective assurance period:** The period from the end of the compliance period through
5 10,000 years following closure of the site.

6
7 **Qualified specialist:** A person, by reason of training or experience, who possesses expertise
8 in a particular field or scientific study (e.g., geomorphologist, seismologist, or chemist).

9
10 **Radionuclide inventory:** The isotopic distribution of radioactive materials by waste class,
11 wasteform, and waste container disposed of in the facility and potentially available for release to
12 the environment.

13
14 **Receptor:** The exposed individual relative to the exposure pathway considered.

15
16 **Receptor scenario:** A type of scenario that describes the FEPs associated with people
17 becoming exposed to radiation.

18
19 **Reviewer:** This document uses the term “reviewer” to include NRC staff reviewers as well as
20 Agreement State reviewers.

21
22 **Risk:** The combined answer to the three questions that consider (1) what can go wrong, (2)
23 how likely it is, and (3) what the consequences might be. In the context of radioactive waste
24 disposal risk refers to probability-weighted radiological doses.

25
26 **Safety assessment:** A systematic analysis of the ability of the site and design to provide the
27 safety functions and meet technical requirements.

28
29 **Safety case:** A collection of information that demonstrates the assessment of the safety of a
30 waste disposal facility. This includes technical analyses, such as the performance assessment
31 and intruder assessment, but also includes information on defense-in-depth and supporting
32 evidence and reasoning on the strength and reliability of the technical analyses and the
33 assumptions made therein. The safety case also includes descriptions of the safety relevant
34 aspects of the site, the design of the facility, and the managerial control measures and
35 regulatory controls.

36
37 **Safety function:** Defined qualitatively as a function through which a component of the disposal
38 system contributes to safety and achieves its safety objective throughout the analyses
39 timeframe.

40 **Scenario:** A future evolution of the disposal site resulting from a subset of FEPs.

41
42 **Scenario development:** The process of incorporating a site's current and future features,
43 events, processes, and their interactions into a scenario. Frequently, a top-down or bottom-up
44 approach is used, or a mixture of the two.

45
46 **Scenario uncertainty:** Uncertainty about the future of the site due to the inherent lack of
47 knowledge about how the site will evolve in time.

48

1 **Sensitivity analysis:** An examination of how the behavior of a system varies with change,
2 usually in the values of the governing parameters. An analysis to investigate the dependencies
3 of the result of the assessment on the alternative input elements (i.e. data, assumption, etc.).
4

5 **Site characterization:** Studies that enable the licensee to sufficiently describe the conditions of
6 the site to evaluate the acceptability of the decommissioning plan.
7

8 **Site closure and stabilization:** Those actions that are taken upon completion of operations
9 that prepare the disposal site for custodial care and that assure that the disposal site will remain
10 stable and will not need ongoing active maintenance.
11

12 **Site stability analyses:** Analyses considering the potential effects of erosion, flooding,
13 seismicity, and other disruptive processes and events on the ability of the disposal facility to
14 meet the performance objectives. In addition, such analyses consider the potential effects of
15 degradation of mechanical properties of containers or other stabilizing man-made features.
16 Stability analyses may be design-based or model-based and may or may not be based on risk
17 considerations.
18

19 **Solubility limit:** The maximum amount of a radionuclide (solute) that can be dissolved per unit
20 of liquid (solvent) under specified conditions (e.g., temperature, pH).
21

22 **Source term:** A conceptual representation of the radionuclide inventory in a disposal site. The
23 quantity of radionuclides expected to be released over time out of a clearly identified boundary
24 (such as the wasteform, container, disposal unit, or facility).
25

26 **Stability:** A term that refers to the ability of the waste and the disposal site to maintain their
27 physical characteristics so that once waste is emplaced, backfilled, and covered, water access
28 to the waste and release of radioactivity is minimized.
29

30 **Surveillance:** Observation of the disposal site for purposes of visual detection of need for
31 maintenance, custodial care, evidence of intrusion, and compliance with other license and
32 regulatory requirements.
33

34 **System description:** A description of the characteristics and interactions, including features
35 and phenomena, of the disposal site and surrounding area to ensure information used to
36 develop the technical analyses and describing the overall disposal system performance have
37 been adequately described.
38

39 **Technical analyses:** Analyses associated with the performance assessment, the intruder
40 assessment, the stability evaluation, and the performance period needed to demonstrate
41 compliance with the Subpart C performance objectives.
42

43 **Total effective dose equivalent (TEDE):** The sum of the deep-dose equivalent (for external
44 exposures) and the committed effective dose equivalent (CEDE) (for internal exposures) (see
45 10 CFR 20.1003).
46

47 **Upscaling:** The modification of data for use at a different scale. Most commonly upscaling
48 transforms data from fine-scale observations for use at a much coarser scale.
49

1 **Uncertainty analysis:** A method of formally assessing, reducing or managing, and
2 documenting the inherent uncertainties of a system. The uncertainties include model
3 uncertainty (which spans conceptual model uncertainty and mathematical model uncertainty),
4 uncertainty about the future of the site, and parameter uncertainty (i.e., uncertainty in values
5 used in the numerical model).
6

7 **Validation (model):** The process of determining the degree to which a model is an accurate
8 representation of the real world from the perspective of the intended uses of the model.
9

10 **Verification (software):** Comparison of the numerical solution generated by the computational
11 model with one or more analytical solutions or with other numerical solutions. Verification of the
12 code ensures that the computer program accurately solves the equations that constitute the
13 mathematical model. Verification of the governing equation demonstrates that it accurately
14 describes the physical processes that occur.
15

16 **Waste acceptance criteria:** Administrative limits, required by 10 CFR Part 61.58 that provide
17 reasonable assurance of compliance with the performance objectives of Subpart C. The criteria
18 include allowable activities and concentrations of specific radionuclides, acceptable wastefrom
19 characteristics and container specifications, and restrictions or prohibitions on waste, materials,
20 or containers that might affect the facility's ability to meet the performance objectives in
21 Subpart C.
22

23 **Waste incidental to reprocessing (WIR):** Wastes that are incidental to the reprocessing of
24 nuclear fuel that can be managed as LLW.
25

26 **Waste stream:** The origin of a low-level waste type or combination of waste types with a
27 particular radionuclide content and distribution independent of its physical characteristics.
28

29 **Waste type:** Radioactive materials such as cloth, wood, plastic, glass, or metal, or other
30 substances obtained from radioactive waste treatment systems, industrial processes, or
31 research experiments. Some examples of waste types are dry solids, dry active waste, ion
32 exchange resins, sorbed liquids, filter cartridges, and activated metals.
33

34 **Wastefrom:** Radioactive waste in its physical and chemical form including any stabilizing or
35 encapsulating material within which it is incorporated.
36

APPENDIX A CHANGES TO 10 CFR PART 61 MADE IN 2015 RULEMAKING

Table A-1 Comparison Table of Current and Proposed 10 CFR Part 61 Regulations

	Protection of the general population from releases of radioactivity (10 CFR 61.41)	Protection of individual from inadvertent intrusion (10 CFR 61.42)	Stability of the disposal site after closure Long-term analyses (10 CFR 61.44)	Defense-in-Depth
Current 10 CFR Part 61 regulations	<ul style="list-style-type: none"> - Pathway analysis - Undefined period of performance - 0.25 mSv (25 mrem) annual whole body dose limit for the protection of the general population - ALARA concept 	<ul style="list-style-type: none"> - Comply with 10 CFR 61.55 - Provide adequate barriers to inadvertent intrusion - Undefined period of performance - No annual dose limit 	Analyses of active natural processes that demonstrate that there will not be a need for ongoing active maintenance of the disposal site following closure.	Implicit in Subpart D technical requirements.
Proposed 10 CFR Part 61 regulations	Within 1,000 Years Following Closure of Disposal Facility (Compliance Period)			
	<ul style="list-style-type: none"> - Performance assessment that estimates peak annual dose that occurs within 1,000 years following closure - 0.25 mSv (25 mrem) annual dose limit for the protection of the general population from the releases of radioactivity that occurs within 1,000 years - ALARA concept 	<ul style="list-style-type: none"> - Comply with LLW acceptance criteria - Provide adequate barriers to inadvertent intrusion - Intruder assessment that estimates peak annual dose that occurs within 1,000 years following closure of disposal facility - 5 mSv (500 mrem) annual dose limit 	Analyses of active natural processes that demonstrate that long-term stability of the site can be ensured and that there will not be a need for ongoing active maintenance of the disposal site following closure.	Analyses that demonstrate the proposed disposal system includes defense-in-depth protections.

Table A-1 Comparison Table of Current and Proposed 10 CFR Part 61 Regulations

	Protection of the general population from releases of radioactivity (10 CFR 61.41)	Protection of individual from inadvertent intrusion (10 CFR 61.42)	Stability of the disposal site after closure Long-term analyses (10 CFR 61.44)	Defense-in-Depth
	Between 1,000 and 10,000 Years Following Closure of Disposal Facility (Protective Assurance Period)			
	<ul style="list-style-type: none"> - Performance assessment that estimates peak annual dose that occurs between 1,000 and 10,000 years following closure of disposal facility - Annual dose shall be below 5 mSv (500 mrem) or a level that is reasonably achievable based on technological and economic considerations for the protection of the general population from releases of radioactivity that may occur between 1,000 and 10,000 years following closure 	<ul style="list-style-type: none"> - Intruder assessment that estimates peak annual dose that occurs between 1,000 and 10,000 years following closure of disposal facility - Annual dose shall be below 5 mSv (500 mrem) or a level that is reasonably achievable based on technological and economic considerations for the protection of the inadvertent intruders from exposures that may occur between 1,000 and 10,000 years following closure 	Analyses of active natural processes that demonstrate that long-term stability of the site can be ensured and that there will not be a need for ongoing active maintenance of the disposal site following closure.	Analyses that demonstrate the proposed disposal system includes defense-in-depth protections.
	After 10,000 Years Following Closure of Disposal Facility (Performance Period)			
	<ul style="list-style-type: none"> - Analyses for 10,000 or more years following closure of disposal facility that demonstrates releases will be 	<ul style="list-style-type: none"> - Analyses for 10,000 or more years following closure of disposal facility that demonstrates exposures will be 		Analyses that demonstrate the proposed disposal system includes defense-in-depth protections.

Table A-1 Comparison Table of Current and Proposed 10 CFR Part 61 Regulations

	Protection of the general population from releases of radioactivity (10 CFR 61.41)	Protection of individual from inadvertent intrusion (10 CFR 61.42)	Stability of the disposal site after closure Long-term analyses (10 CFR 61.44)	Defense-in-Depth
	minimized to the extent reasonably achievable for the protection of the general population - Analyses only apply for disposal sites containing long-lived radionuclides exceeding concentrations listed in table A of 10 CFR 61.13(e), or if necessitated by site-specific conditions - Analyses that demonstrate how the facility has been designed to limit long-term releases.	minimized to the extent reasonably achievable for the protection of inadvertent intruders - Analyses only apply for disposal sites containing long-lived radionuclides exceeding concentrations listed in table A of 10 CFR 61.13(e), or if necessitated by site-specific conditions - Analyses that demonstrate how the facility has been designed to limit long-term exposures to an inadvertent intruder.		

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APPENDIX B HAZARD MAPS

The NRC staff created hazard maps related to the features and phenomena of the 10 CFR 61.50 criteria. The hazard maps presented in this appendix provide an illustration of features, events, and processes (FEPs) related to 10 CFR 61.50 site suitability criteria. The maps cannot be displayed in this document at sufficient size to be used to determine if any specific location would be impacted by one of these phenomena. The figures provide an illustration of potentially impacted areas.

The figures should not be used by regulators to prohibit disposal because the resolution of the maps and the precision and accuracy of the techniques used to generate them may not be sufficient for site-specific evaluations. However, regulators should use the maps to determine when greater review effort and more technical basis should be expected for the licensee's site-specific evaluation. In addition, the data used to produce these maps could be used, via Geographic Information System (GIS) software, to perform screening-level analyses of the FEPs.

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.

1 Figure B-5 – The source is hydrology data compiled from various sources and provided by
2 ESRI. The figure is based on the categories provided in the referenced data sources. There
3 could be other data categories not in the ESRI data source that might be areas of previous
4 flooding (ESRI, 2008a; ESRI, 2008b).
5

6 Figure B-6 through B-9 - The data were available for download from the websites listed in the
7 references cited on the figure caption. Thirty five tiles of data that covered the continental U.S.
8 were used. Each tile of data contained files representing the extent of glaciation at various
9 times during the quaternary. There were four general time periods covered in most cases: the
10 Younger Dryas, the Late Weichselian (Wisconsinian), the Early-Middle Weichselian, and the
11 maximum limit of Pleistocene glaciation. For some tiles there were separate files for various
12 features: ice sheets, mountain glaciers, and basin glaciers. Sometimes they were all combined
13 into one file with a field in the attribute table which signified which type of feature it was.
14 Sometimes there were separate data files for the work of from more than one author. Not all
15 authors studied the entire continental U.S. The files representing like datasets were merged for
16 all of the tiles and those files were clipped to the boundary of the continental U.S. plus Great
17 Lakes. Areas in each file that represent ice covered areas for that particular time stamp are
18 displayed as black on the map. By stacking all of the files from various authors and features on
19 top of each other in the map, the maximum extent of glaciation for the period covered by these
20 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)

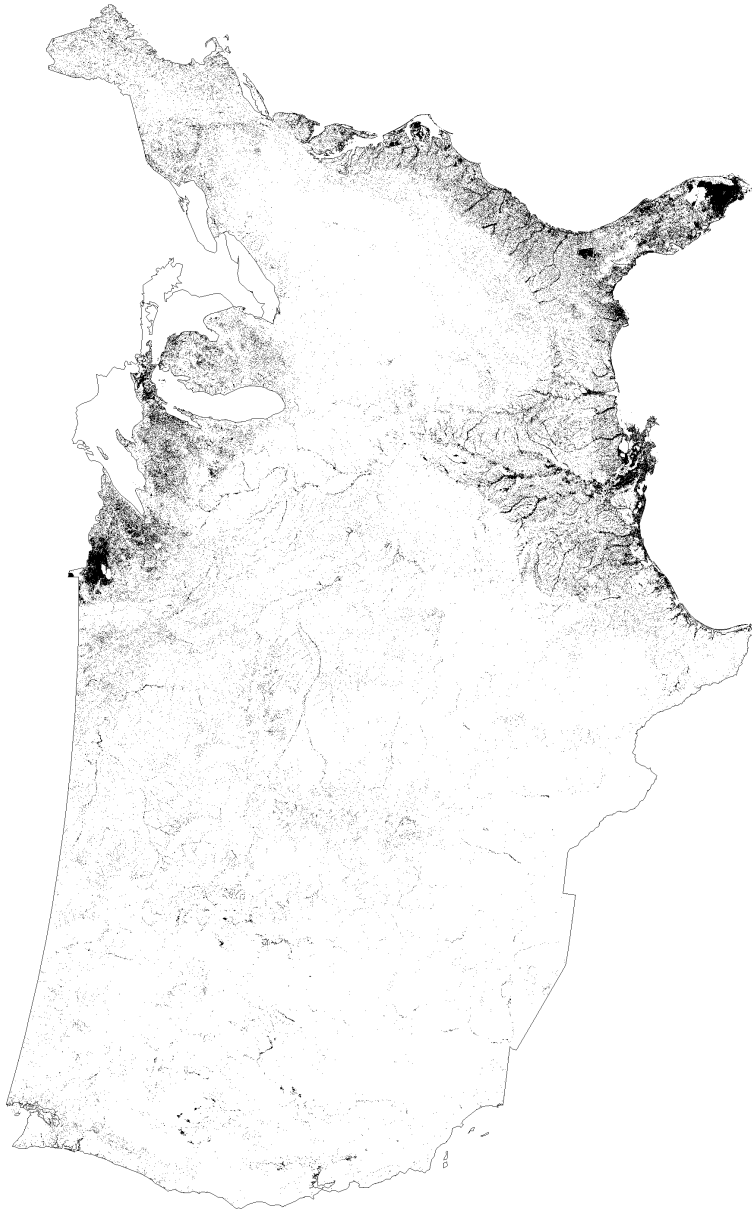


Figure B-2: Approximate area of current wetlands. Proposed sites located near these areas may require additional site characterization and analysis. Wetland areas in the future may change (USGS, 2011)



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)

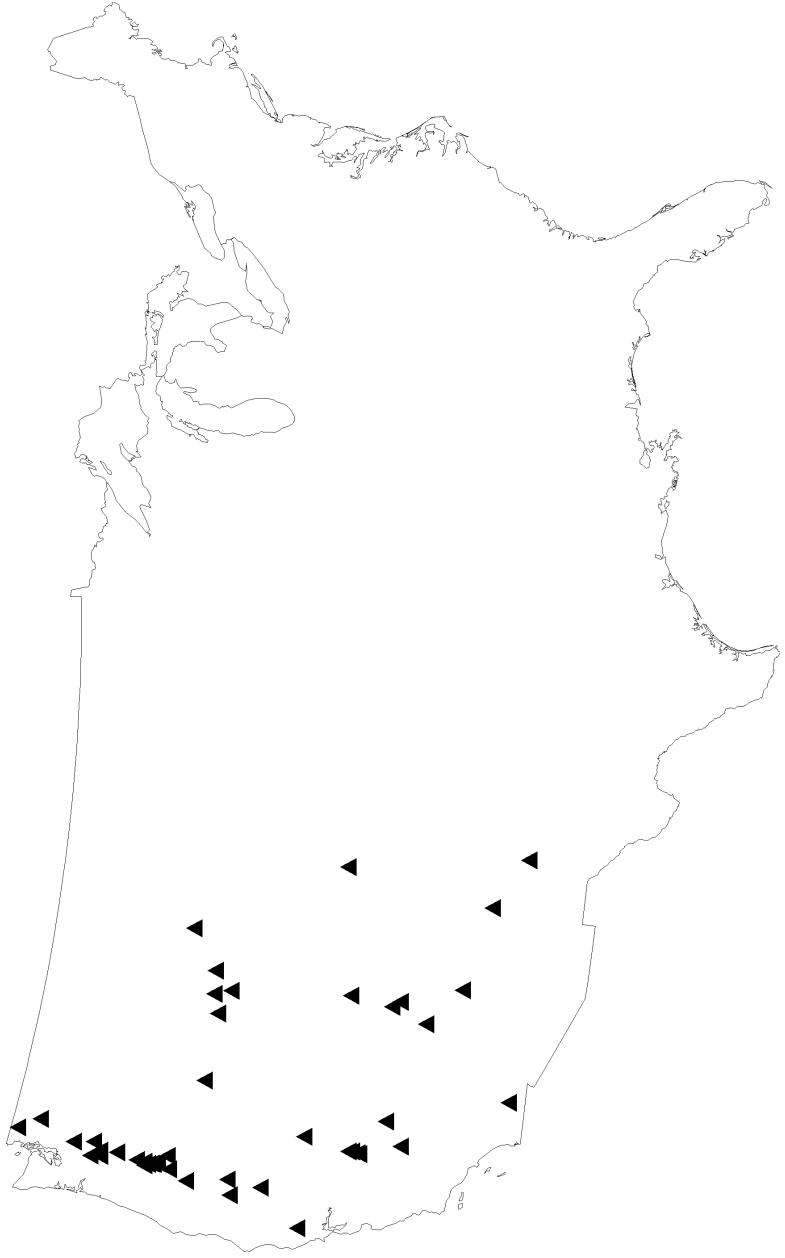


Figure B-6: Approximate locations of Holocene volcanic activity. Proposed sites located near these locations may require additional analysis and evaluation (Siebert and Simkin, 2002)



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



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



Figure B-9: Approximate area covered by glaciers during the last three glacial periods of the current Quaternary ice age, i.e., the Wisconsin, Illinoian, and Pre-Illinoian 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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1 **APPENDIX C**
2 **GENERIC FEATURES, EVENTS, AND PROCESSES LIST FOR**
3 **NEAR-SURFACE DISPOSAL OF LOW-LEVEL RADIOACTIVE**
4 **WASTE**
5

6 The NRC staff has developed a generic FEPs list that can be used by reviewers, applicants,
7 licensees, and other interested stakeholders involved with preparation and review of technical
8 analyses conducted to support licensing of a near-surface low-level radioactive waste (LLW)
9 disposal facility. The NRC staff consulted numerous references to develop (1) a comprehensive
10 list of FEPs, and (2) a smaller set of FEPs (or “starter list”) that need to be analyzed and
11 screened based on requirements in 10 CFR Part 61 and are usually considered to be essential
12 to development of performance assessment (PA) analyses. The starter FEP list should not be
13 considered a complete FEP list. Rather, it is a core list of FEPs that any LLW PA should
14 consider for screening. There are various methods of screening FEPs as described in Section
15 2.0. The level of technical analysis needed to justify exclusion of a required FEP or needed to
16 evaluate the impact of an included (or “screened in”) FEP (or set of FEPs) can vary. The level
17 of effort expended on disposition or evaluation of the FEP(s) should be commensurate with the
18 expected risk-significance of the FEP (or group of FEPs that form a central or alternative
19 scenario). A complete set of site-specific FEPs can only be developed from an adequate
20 understanding of the disposal system that is gained through site characterization and review of
21 detailed facility designs. Development and evaluation of FEPs is considered an iterative
22 process, beginning first with evaluation of a central scenario that incorporates all of the key
23 FEPs that best represent the dynamic system being studied. Following initial analyses,
24 alternative scenarios that might include potential disruptive events should also be considered,
25 as appropriate; to ensure that potential vulnerabilities in disposal system performance are
26 identified and adequately addressed. As-emplaced conditions (including final engineered
27 barrier configurations and waste allocation), monitoring, and other data developed following
28 initial PA preparation, should also be considered to ensure that the results of the PA adequately
29 assess the risk of the disposal facility. The starter list of FEPs that should be addressed in LLW
30 PAs is provided in Table C-1.
31
32

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) Temperature cycling or extremes Freeze thaw cycling

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

Type	FEP
	Frost action Wet/dry cycling Salt action Oxidation Acid attack Weathering Fracturing (via mechanical or chemical/reaction) Cementitious material degradation Geosynthetic degradation processes Plugging of drainage layers Degradation of clays (e.g. dessication) Polymer degradation Seismic-induced degradation
	Internal degradation processes, to waste and disposal units: Biodegradation Reaction – incompatible materials Thermodynamic instability Excessive void space – subsidence Radiation damage Dissolution Internal stress generation
	External degradation processes, interaction of system with environment
	Geochemical evolution (disposal unit, disposal site, surrounding environment)
	Geochemistry – speciation, solubility, sorption, etc.
	Interactions of environment and disposal system
	Biological driven release (plant uptake, burrowing animals, 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
	Geomorphology
	Surface geologic processes – mass wasting, subsidence, slope failure, etc.
	Dynamic change to geology (e.g. sinkhole formation)
	Loading and differential settlement

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

Type	FEP
	Pedogenesis
	Tectonic processes
	Groundwater transport
	Gas transport
	Soil transport (fluvial, aeolian)
	Colloid transport
	Dose assessment processes (e.g. drinking water consumption, soil build-up, resuspension)
	Dynamic processes (e.g. natural temporal variability, seasonal effects, episodic changes, barometric pumping)
Event	Explosion
	Fire
	Inadvertent human intrusion (habitation, drilling, resource exploration)
	Accident – operational or external
	Dam failure
	Aircraft crash
	Tectonic events: Seismic (including earthquakes) Volcanic Tsunami
	Tornado
	Hurricane

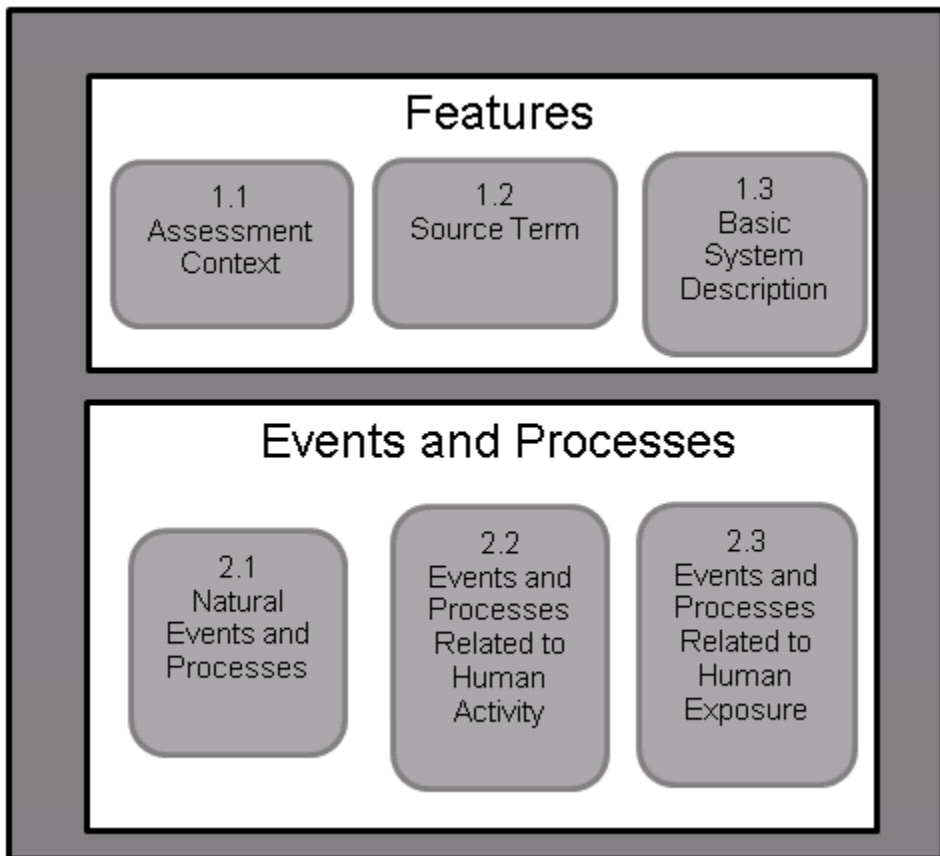
1
2 As discussed above, a comprehensive generic FEPs list appropriate for near-surface disposal
3 of low-level radioactive waste was developed for use by reviewers, applicants, licensees, and
4 other interested stakeholders. A number of references were consulted during development of
5 this list (NEA, 2000; NEA, 2006; IAEA, 2003, BIOMOVs II, 1996; Art, 2013; Neptune, 2011;
6 SRS, 2012a; SRS, 2012b). Some of the reference FEPs are not expected to be risk-significant
7 during the time periods of interest for disposal of most LLW or are considered outside the scope
8 of the 10 CFR Part 61 regulatory framework. An effort was made to identify classes of these
9 FEPs. For those FEPs sources that screened FEPs in or out (e.g., BIOMOV and site-specific
10 FEPs lists), the rationale for exclusion of the FEP was considered in determining whether to list
11 the FEP in the generic FEPs list. It is important to note that although a project-specific FEP may
12 have been “screened out”, if the FEP was considered potentially applicable to near-surface LLW
13 disposal, it was included in the generic FEP list. Although screening approaches and the results
14 of screening are summarized below, it is important to note that no effort was made to evaluate
15 the adequacy of FEP screening processes discussed, nor the completeness of project-specific
16 FEP lists.

17
18 The comprehensive, generic FEPs list is structured after the Improvement of Safety
19 Assessment Methodologies (ISAM) and Nuclear Energy Agency (NEA) FEPs lists described in
20 more detail below. FEPs that may be considered unlikely during the compliance period but may
21 become increasingly more likely over time are flagged as “long-term” FEPs. If a FEP is
22 designated a “long-term” FEP the applicability of the FEP for a specific site should be
23 considered by licensees when performance period analyses are required. Although some FEPs
24 from the reference sources are not explicitly listed in the generic FEP list, one can assume that
25 the FEP should be considered unless it is clearly linked to a category of FEPs that are not
26 considered important for near-surface waste disposal.

1 Reference sources used to create the generic FEPs list include databases developed by
2 international standards setting organizations, as well as several site-specific applications for
3 low- and high-level radioactive waste disposal facilities (or repositories) in the United States and
4 indirectly, Europe¹. A brief description of each of these data sources is provided first below.

5
6 **BIOMOVs II**

7 A structured, generic biosphere FEP list was developed by the BIOMOVs II Reference
8 Biospheres Working Group. BIOMOVs is an international study to test models designed to
9 predict the environmental transfer and bioaccumulation of radionuclides and other trace
10 substances. The BIOMOVs II FEP list was developed specifically for application to the
11 calculation of annual individual doses arising at an inland site from long-term release of
12 radionuclides to groundwater. The list is, nonetheless, relevant to a wide range of
13 assessments. The developers recognized that the list may not include sufficient detail for any
14 specific project or assessment. Additionally, definitions may not be universally applicable. The
15 structure of the FEPs list is provided in Figure C-1. The expanded FEPs list includes
16 approximately 140 FEPs.



17 **Figure C-1 Structure of BIOMOVs FEPs List**

18

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.

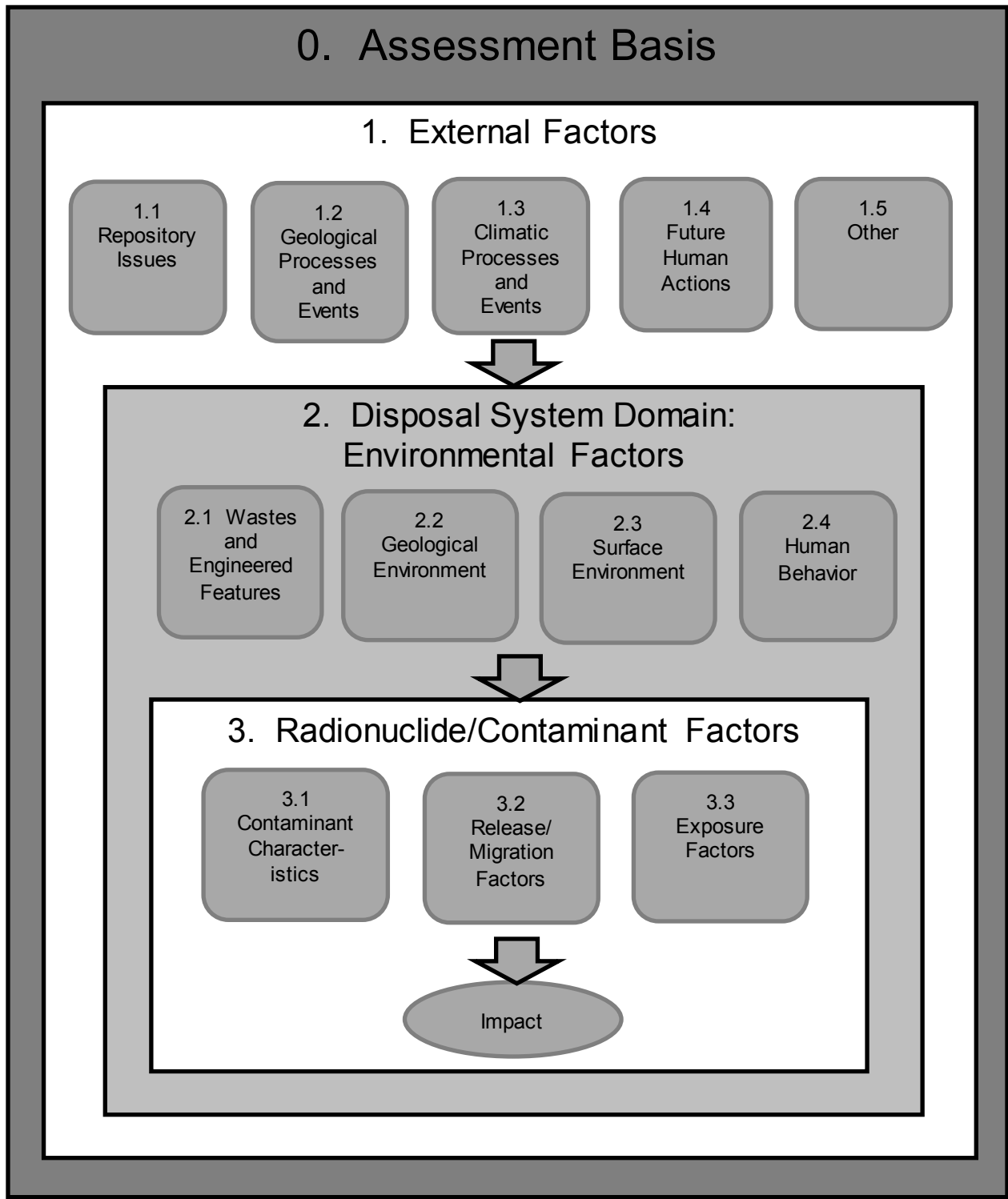
The database was developed by the NEA FEP Database Working Group that included representatives from seven, Organization for Economic Cooperation and Development (OECD)/NEA countries. Version 2.1 of the database contains over 1650 project-specific FEPs² from 10 projects (2006). Two additional project-specific FEPs lists were added: (i) SCK-CEN Catalogue of Events, Features and Processes for the Mol Site in Belgium and (ii) Encyclopedia of FEPs for the Swedish SFR and Spent Fuel Repositories. Additional details on the project specific FEPs lists and additional functionality were added to the database. The NEA international FEPs list can be considered a generic, high-level FEPs list from which project-specific FEPs could be developed or categorized. Project-specific FEPs available in the database are cross-walked back to the categorical FEPs comprising the international FEPs list. The major categories of the NEA international FEPs list are provided in Figure C-2. The international FEPs list has 4 layers with the 3 inner layers in Figure C-2 further subdivided into additional categories. Not listed in Figure C-2 are individual FEPs for each subcategory.

IAEA ISAM

In 1997, the IAEA launched a coordinated research project on Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM) to critically evaluate, enhance, and provide confidence in the approaches and tools used for post-closure safety assessments of near-surface radioactive waste disposal facilities. As part of the ISAM project, the NEA international FEPs list was modified for near surface disposal facilities. For example, some of the NEA FEP definitions and comments associated with the FEPs were altered to be more representative of near surface conditions. The ISAM FEPs list was intended to be a user-friendly list. The ISAM FEPs list was also intended to be a comprehensive, initial list from which FEPs applicable to any specific site could be developed. Because the NEA list was extensively reviewed for completeness for geologic systems and the ISAM FEPs lists was based on the NEA FEPs list, the developers of the ISAM FEPs list reasoned that users should have additional confidence in the comprehensiveness of the ISAM FEPs list. Additionally, experience with both specific near surface disposal facilities and FEPs lists developed and applied in the ISAM test cases was used in the development of the ISAM FEPs list. The hierarchy of the ISAM FEPs list is similar to that of the NEA international FEPs list in Figure C-2³.

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.



1
2 **Figure C-2 Structure of the NEA FEPs list**

1 BIOMASS

2
3 Changes were made to the organization of the BIOMOVs II list described above in developing
4 the BIOMASS FEPs list. These changes include the following:

- 5
6 • A clearer distinction between FEPs related to basic elements of the assessment context
7 and those related to the biosphere system, radionuclide transport and radiation
8 exposure.
- 9 • The expression of intrinsic phenomena relating to the biosphere system in terms of
10 characteristics of the system, rather than the behavior of radionuclides within the
11 system. Those FEPs that relate to radionuclide behavior can (where necessary) be
12 incorporated in the respective definitions. FEPs that are related solely to the presence
13 of radionuclides within the system (e.g. radiation exposures) are then clearly identified
14 under a separate heading.
- 15 • Experience gained with the application of the reference biosphere methodology since
16 BIOMOVs II, which has helped to amplify certain details of the original list and led to the
17 incorporation of additional FEPs.

18
19 Department of Energy (DOE) Hanford site

20
21 The Hanford Site is an approximately 586 mi² area north of the city of Richland within the
22 semiarid Pasco Basin of the Columbia Plateau in southeastern Washington State. Hanford
23 occupies a relatively undeveloped area of shrub-steppe (a drought-resistant, shrub and
24 grassland ecosystem) that contains a rich diversity of plant and animal species. The area has
25 been protected from disturbance, except for fire, over the past 60 years. This protection has
26 allowed plant species and communities that have been displaced by agriculture and
27 development in other parts of the Columbia Basin to thrive at the Hanford Site. The Columbia
28 River flows eastward through the northern part of the Hanford Site and then turns south, forming
29 part of the eastern site boundary. Other important rivers near the Hanford Site are the Yakima
30 River to the south and southwest and the Snake River to the east. The Cascade Mountains,
31 which are about 160 km (100 mi) to the west, have an important effect on the climate of the
32 area.

33
34 In 1943, the U.S. Army Corps of Engineers created the Hanford Site from small farming areas
35 along the Columbia River to locate facilities used to produce nuclear weapon materials for
36 World War II. Since then, the major activities on the Hanford Site have been controlled by DOE
37 and its predecessors. Current major programs at the Hanford Site are dedicated to waste
38 management, environmental restoration, long-term stewardship, and research and
39 development. Fuel reprocessing, plutonium and uranium separation, plutonium finishing, and
40 waste management, including treatment, storage, and disposal activities have been conducted
41 in the 200 Area of the site.

42
43 There are a total of 177 underground tanks located in the 200 Area of the site used to store
44 reprocessed, liquid high-level waste from reactor operations and other site activities. DOE has
45 initiated the process of retrieving, treating, and disposing of radioactive mixed waste from 149
46 underground single-shell tanks that do not have secondary containment. DOE Hanford
47 prepared a performance assessment (PA) to support closure of these tanks. In 2009, DOE
48 Hanford initiated a scoping process to assist with updating the PA to support tank closure. An
49 extensive FEPs list was developed as part of this scoping process. Due to lack of funding the
50 scoping process was curtailed; however, the draft list of FEPs developed during Hanford PA
51 scoping was considered in this study.

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Clive, Utah Site

The Clive, Utah low-level waste disposal facility is operated by Energy Solutions. Energy Solutions prepared a PA to evaluate the risk of disposal of depleted uranium (DU) waste. To support PA development, Energy Solution developed a list of FEPs. Neptune (2011) documents and examines the universe of FEPs that may apply to the disposal of DU waste at the Clive Facility. The identification of FEPs for use in the Clive facility PA was an iterative process that began with compilation of an exhaustive list of candidate FEPs that could affect the long-term performance of the low-level waste disposal facility. Table C-2 lists the reference sources considered in developing the initial list of FEPs. As an initial step, all potentially relevant FEPs from a variety of reference sources were collected (e.g., Yucca Mountain Project, the Waste Isolation Pilot Plant, and several foreign radioactive waste projects). The initial list from external sources was modified as additional FEPs were identified that are specific to the Clive facility. Approximately 980 FEPs were identified.

This exhaustive compilation of FEPs led to significant redundancy across the original sources. Redundancy was addressed by the modification of the candidate list of FEPs through normalization (removal of redundant FEPs) and assignment of FEPs categories (groupings of common FEPs). This consolidation process reduced the total number to 135 unique FEP groupings. These 135 unique FEP groupings were binned into 18 major categories.

Of the 135 FEP groupings, 67⁴ FEP groupings were retained for further consideration and 68⁵ 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).

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.

1 **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. <i>The Joint SKI/SKB Scenario Development Project</i> . SKB-TR8 9-35, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.
WIPP	Burkholder, H.C., 1980. <i>Waste Isolation Performance Assessment—A Status Report</i> , in <i>Scientific Basis for Nuclear Waste Management</i> , Ed. C.J.M. Northrup, Jr., Plenum Press, New York, NY, Vol. 2, p. 689-702.
WIPP	Guzowski, R.V., 1990. <i>Preliminary Identification of Scenarios That May Affect the Escape and Transport of Radionuclides From the Waste Isolation Pilot Plant, Southeastern New Mexico</i> , SAND89-7149, Sandia National Laboratories, Albuquerque, NM.
NTS	Guzowski, R.V., and G. Newman, 1993. <i>Preliminary Identification of Potentially Disruptive Scenarios at the Greater Confinement Disposal Facility, Area 5 of the Nevada Test Site</i> , SAND93-7100, Sandia National Laboratories, Albuquerque, NM.
NTS	Hertzler, C.L., and C.L. Atwood, 1989. <i>Preliminary Development and Screening of Release Scenarios for Greater Confinement Disposal of Transuranic Waste at the Nevada Test Site</i> , EGG-SARE-8767, EG&G Idaho, Inc., Idaho Falls, ID.
Hypothetical Columbia Plateau Repository	Hunter, R.L., 1983. <i>Preliminary Scenarios for the Release of Radioactive Waste From a Hypothetical Repository in Basalt of the Columbia Plateau</i> , SAND83-1342 (NUREG/CR-3353), Sandia National Laboratories, Albuquerque, NM.
WIPP	Hunter, R.L., 1989. <i>Events and Processes for Constructing Scenarios for the Release of Transuranic Waste From the Waste Isolation Pilot Plant, Southeastern New Mexico</i> , SAND89-2546, Sandia National Laboratories, Albuquerque, NM.
HLW Repository	IAEA, 1983. <i>Concepts and Examples of Safety Analyses for Radioactive Waste Repositories in Continental Geological Formations</i> , Safety Series Report No. 58, IAEA, Vienna.
HLW Repository	Koplik, C.M., M.F. Kaplan, and B. Ross, 1982. <i>The Safety of Repositories for Highly Radioactive Wastes</i> , <i>Reviews of Modern Physics</i> , Vol. 54, No. 1, p. 269-310.
HLW Repository (Canada)	Merrett, G.J., and P.A. Gillespie, 1983. <i>Nuclear Fuel Waste Disposal: Long-Term Stability Analysis</i> , AECL-6820, Atomic Energy of Canada Limited, Pinawa, Manitoba.
NEA Working Group	NEA (Nuclear Energy Agency), 1992. <i>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</i> , Nuclear Energy Agency, Paris, France.
NEA Working Group	NEA, 2000. <i>Features, Events, and Processes (FEPs) for Geologic Disposal of Radioactive Waste. An International Database</i> . Nuclear Energy Agency, Organization for Economic Cooperation and Development.

2 [†] References for Andersson et al. (1989), Burkholder (1980), Guzowski (1990), Hertzler and Atwood
3 (1989), Hunter (1983), Hunter, (1989), IAEA (1983), Koplik et al. (1982), Merrett and Gillespie, NEA
4 (1992) and Prij et al. (1991) were found in Guzowski and Newman (1993).

5

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
1	Model Settings	Model Parameterization
2		Period of Performance
3		Regulatory Requirements
4		Spatial Domain
5	Geological	Diagenesis
6		Gas or Brine Pockets
7		Landslide
8		Local Subsidence
9	Geochemical	Geochemical Effects
10	Hydrogeological	Denudation
11		Erosion
12		Erosional Transport
13		Hydrogeological Effects
14		Sedimentation
15		Subrosion
16	Hydrology	Groundwater Transport
17		Hydrological Effects
18		Inundation
19		Flooding
20		Surface Water Transport
21	Meteorology	Frost Weathering
22		Meteorology
23		Resuspension
24		Atmospheric Dispersion
25		Tornado
26	Marine	Coastal Processes
27		Hurricanes
28		Insolation
29		Marine Effects
30		Tsunami
31	Climate Change	Climate Change
32		Lake Effects
33		Wave Action
34		Glacial Effects
35		Permafrost
36	Tectonic/Seismic/Volcanic	Geophysical Effects
37		Breccia Pipes
38		Diapirism
39		Discontinuities
40		Earthquake
41		Faulting
42		Fracturing
43		Geological Intrusion
44		Hydraulic Fracturing

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings	
45		Instrusion Into Accumulation Zone in the Biosphere	
46		Isostatic Effects	
47		Lava Tubes	
48		Orogeny	
49		Regional Subsidence	
50		Seismic Effects	
51		Tectonic Effects	
52		Volcanism	
53		Celestial	Meteorite Impact
54		Natural Processes	Microbial Effects
55	Radiological Effects		
56	Wildfire		
57	Other Natural Processes	Ecological Changes	
58		Gas Generation	
59		Pedogenesis	
60		Radioactive Decay and In-growth	
61		Radon Emanation	
62		Reconcentration	
63	Human Processes	Anthropogenic Climate Changes	
64		Community Development	
65		Excavation	
66		Explosions	
67		Human-Induced Processes	
68		Human-Induced Transport	
69		Inadvertent Human Intrusion	
70		Inhabitation	
71		Institutional Control	
72		Land Use	
73		Post-Closure Subsurface Activities	
74		Accidents During Operations	
75		Climate Control	
76		Closure Failure	
77		Fire	
78		Fisheries	
79		Geothermal Energy Production	
80		Injection Wells	
81		Intentional Intrusion	
82		Investigation	
83		Irrigation	
84		Monitoring	
85		Nuclear Testing	
86		Operational Effects	
87		Operational Error	

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
88		Quality Control
89		Resource Extraction
90		Sabotage
91		Unplanned Events
92		War
93		Waste Recovery
94		Water Resource Management
95		Weapons Testing
96		Containerization
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	Biologically-Induced Transport
110		Colloid Transport
111		Contaminant Transport
112		Diffusion
113		Dilution
114		Dispersion
115		Dissolution
116		Dust Devils
117		Gas Transport
118		Infiltration
119		Local Geology
120		Preferential Pathways
121		Gas Intrusion
122		Convergence of Opening
123		Design Error
124		Material Defects
125		Mechanical Effects
126		Release of Stored Energy
127		Repository Seals
128	Exposure	Animal Ingestion
129		Dosimetry
130		Exposure Media
131		Human Behavior

Table C-3 Clive Facility FEP Groupings and FEPs

ID	FEP Category	FEP Groupings
132		Human Exposure
133		Ingestion Pathways
134		Inhalation Pathways
135		Agriculture

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DOE Savannah River Site (SRS)

SRS is a 780 km² (300 mi²) DOE facility located approximately 12 miles south of Aiken, South Carolina, and 15 miles southeast of Augusta, Georgia. The SRS region is characterized as a humid subtropical climate with relatively short, mild winters and long, warm, and humid summers. Summer-like conditions typically last from May through September, when the area is frequently under the influence of a western extension in the semi-permanent Atlantic subtropical anticyclone (i.e., the 'Bermuda' high). The influence of the Bermuda high begins to diminish during the fall as continental air masses become more prevalent, resulting in lower humidity and more moderate temperatures. Less than one-third of winter days have minimum temperatures below freezing on average, and days with temperatures below 20°F are infrequent. Measurable snowfall occurs an average of once every two years.

Operation at SRS began in 1951. The primary use for the site was the production of nuclear material for national defense. Between 1954 and 1986, DOE generated significant quantities of radioactive waste from the reprocessing of spent nuclear fuel and to a lesser extent from the production of targets for nuclear weapons and material for space missions. This waste was stored in 51 underground tanks located in two tank farms: F-Tank Farm (FTF) contains 22 tanks and H-Tank Farm houses 29 tanks. DOE plans to clean the tanks and stabilize the waste residuals in a cementitious wasteform. DOE also plans to dispose of relatively low-activity salt waste retrieved from the tanks in the saltstone disposal facility. DOE has prepared PAs to demonstrate that the stabilized waste remaining in the tank farms and the waste disposed of in the saltstone disposal facility can meet performance objectives for low-level waste disposal. DOE prepared an *ex post facto* FEPs analysis to provide support for its compliance demonstrations.

The initial, SRS FEPs list included 245 FEPs drawn from five different reference sources listed in Table C-4. The initial 245 FEPs were then binned into six categories listed in Table C-5.

1 **Table C-4 SRS FEP List Reference Sources**

FEPs List	Source Document	Total Number of FEPs
ISAM	<i>Safety Assessment Methodologies for Near-Surface Disposal Facilities</i> , Results of a Coordinated Research Project, Volume 1 [ISBN 92-0-104004-0]	141
UFD	<i>Features, Events, and Processes for the Disposal of Low Level Radioactive Waste FY2011 Status Report</i> [FCRD-USED-2011-000297]	449
YMP	<i>Features, Events, and Processes for the Total System Performance Assessment: Analyses</i> [ANL-WIS-MD-000027 REV 0]	374
DGR	<i>Deep Geologic Repository for OPG's Low and Intermediate Level Waste, Post-Closure Safety Assessment (Volume 1): Features, Events and Processes</i> [NWMODGR-TR-2009-05]	299
SKI	<i>Encyclopedia of Features, Events and Processes (FEPs) for the Swedish SFR and Spent Fuel Repositories</i> [SKI Report 02:35]	120

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3

1 **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

2
3 In addition to consolidation of the 5 FEPs list reference sources, DOE included 17 additional
4 FEPs evaluated in SRS PAs leading to a total of 262 FEPs. Next, the list of 262 FEPs was
5 screened⁶. The SRS FEPs screening team performed screening in two phases. During the first
6 phase, team members independently applied the FEPs screening criteria⁷ via survey. The
7 independent survey results were collected and a subset of FEPs was “screened in” or “out”
8 based on the results. Those FEPs with relatively more ambiguous results (i.e., survey results
9 indicated that FEP should be considered further) were discussed in the second phase. At the

⁶ This is true except for 46 programmatic FEPs that would not be subject to screening. These FEPs are listed in Table 4.0-1 of SRR-CWDA-2012-00011, Revision 0.

⁷ Criteria were based on the perceived probability of occurrence within 10,000 years and the perceived consequence relative to final PA results.

1 start of Phase 2, 142 FEPs remained. The FEPs that were “screened out” in Phase 1 and 2 are
2 listed in Table C-6.

3

4 A total of 230 FEPs remained after Phase 2 screening. SRR-CWDA-2012-00022 crosswalks
5 remaining FEPs to the FTF PA to ensure all relevant FEPs were addressed.

6

7

1 **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

2

1 Generic FEPs List
2

3 The ISAM and NEA international FEP list structure illustrated in Figure C-2 above was retained
4 in constructing a comprehensive, generic FEP list applicable to near-surface disposal of LLW.
5 Because the ISAM FEP list modified the NEA FEP list to be more applicable to near-surface
6 disposal facilities, the ISAM FEP category titles are specifically listed in the generic FEP list.
7 However, some FEPs of the ISAM FEPs are not expected to be risk-significant during the time
8 periods of interest for disposal of most LLW in the United States or are considered outside the
9 scope of the 10 CFR Part 61 regulatory framework. These FEPs that are considered less
10 relevant for near-surface disposal of LLW are listed in Table C-7. The remaining ISAM FEPs
11 represent the major FEP groupings in the generic FEPs list (see column 1).
12

13 The generic FEPs list comprises three separate tables: (i) assessment context or operational
14 factors (see Table C-8) used to develop FEPs presented in Tables C-9 and C-10, (ii) FEPs to
15 analyze or screen to construct central and alternative scenarios presented in Table C-9, and (iii)
16 FEPs to analyze or screen for receptor scenarios presented in Table C-10. Table C-8 factors
17 are not FEPs per se, but assessment context (e.g., purpose of the assessment), operational
18 factors, and site characterization or monitoring activities may dictate the types and scope of
19 FEPs considered in a technical assessment. Therefore, Table C-8 factors are listed and
20 expected to be valuable considerations in the development of project-specific FEPs.
21

22 FEPs that may be considered unlikely during the compliance period or protective assurance
23 period but may become increasingly more risk-significant over time are flagged “long-term” in
24 column 3 of Tables C-9 and Table C-10 (no assessment context factors are marked long-term).
25 If the “long-term” column is marked in column 3, the applicability of the FEPs for a specific site
26 should be considered when performance period analyses are required for that site. Although
27 some FEPs from the reference sources are not explicitly listed in Tables C-7 through C-10, one
28 can assume that the FEP should be considered unless it is clearly linked to a category of FEPs
29 that are not considered applicable for near-surface waste disposal listed in Table C-7.

30 Reviewers, applicants, licensees, and other interested stakeholders should find the level of
31 detail provided in tables sufficient to understand the scope of FEPs that should be considered
32 for any site with many examples provided in the last column (column 4); however, the generic
33 FEP list should not be considered an exhaustive list that would encompass every potentially
34 applicable FEP that may be important for a particular site. Likewise, not every FEP listed in
35 Tables C-8 through C-10 would need to be considered by a licensee.
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Table C-7 FEPs Less Relevant for Near-Surface Disposal of LLW in the United States

Excluded FEP	ISAM ID	Rationale
Future human action assumptions ¹	0.05	The scope of this FEP is limited. Future societal and technology development will occur, but is difficult to predict. Therefore, unnecessary speculation about future human actions should be avoided. The uncertainty associated with future human actions is accounted for in the technical analyses by using reasonably conservative receptor scenarios.
Future human behavior (target group) assumptions ¹	0.06	The scope of this FEP is limited. Future human behavior is difficult to predict. Unnecessary speculation about future human behavior should be avoided.
Retrievability	1.1.13	LLW disposal facilities in the United States are not designed for retrievability.
Orogeny and related tectonic processes at plate boundaries	1.2.01	Orogeny and related tectonic processes at plate boundaries are only expected to be important for near-surface disposal facilities if very long performance periods are evaluated.
Anorogenic and within-plate tectonic processes (Deformation, elastic, plastic, and brittle)	1.2.02	Anorogenic and within-plate tectonic processes are only expected to be important for near-surface disposal facilities if very long performance periods are evaluated.
Metamorphism	1.2.05	Metamorphism is not expected to be important for near-surface disposal facilities or in the timeframes of interest.
Diagenesis ²	1.2.08	Diagenesis is not expected to be important for near-surface disposal facilities or in the timeframes of interest.
Human influences on climate including ozone depletion, global warming, and greenhouse effect.	1.4.01	Future anthropogenic impacts on climate change are difficult to predict and are covered under natural climate change.
Motivation and knowledge issues (inadvertent/deliberate human actions)	1.4.02	The scope of this FEP is limited. Advertent intruders are not protected under 10 CFR Part 61.

Table C-7 FEPs Less Relevant for Near-Surface Disposal of LLW in the United States

Excluded FEP	ISAM ID	Rationale
Pollution (as it impacts site performance, radionuclide mobility, or monitoring)	1.4.07	The scope of this FEP is limited. Unnecessary speculation about future pollution should be avoided. Current and reasonably foreseeable pollution should be considered.
Social and institutional developments	1.4.11	The scope of this FEP is limited. Unnecessary speculation regarding future human actions and behavior should be avoided such as changes in demography, land use, controls, and regulatory requirements that may not need to be evaluated. Loss of control of a site due to loss of records or societal memory should be included and is considered in the inadvertent intruder analysis.
Technological developments	1.4.12	The scope of this FEP is limited. Technological developments are likely to occur but difficult to predict. Unnecessary speculation regarding future technological advances should be avoided (e.g., cure for cancer, technological advances in food production).
Explosions and crashes	1.4.14	The scope of this FEP is limited. For example, deliberate or malicious human actions may not need to be considered.
Meteorite impact ³	1.5.1	Considered unlikely.
Species evolution ³	1.5.2	Expected to be of limited significance in the timeframes of interest and with unknown impact.
Miscellaneous and FEPs of uncertain relevance ³	1.5.3	Items in this category are not considered likely or significant to near-surface, LLW disposal (e.g., extraterrestrial activity, dust, changes in magnetic field, change in tidal processes).
Non-radiological toxicity/effects	3.3.08	Non-radiological effects are not considered.
¹ FEP of limited scope. ² Table C-9 includes a portion of this FEP (pedogenesis) that may need to be considered. ³ NEA FEPs that are excluded from the ISAM FEPs list.		

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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 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)
Spatial domain of concern ⁸	0.03		Safety Effects Beyond Periods of Control (beyond institutional control period) (SRS 1.1.07) Assessment Domain/Spatial Domain of Concern (HAN 0.4.02, SRS 1.1.08, CLV 4)
Facility ⁹ assumptions (e.g., assumptions regarding the success of facility closure and any changes to design, construction, or waste emplacement)	0.04		Repository System (BMA 2.1.4) Site, Context (BMA, 2.1.5, BMO 1.1.4) Facility Type (BMO 1.1.3) Disposal Facility Assumptions (HAN 0.4.09) Facility Factors (life cycle of disposal facility) (SRS 3.1.03)
Dose response assumptions ¹⁰	0.07		Dose Response Assumptions (HAN 0.4.07)
Assessment purpose	0.08		Assessment Purpose (e.g., site selection and characterization, design, compliance, WAC, corrective action, confidence) (BMA 2.1.1, BMO 1.1.1, HAN 0.1, SRS 1.1.02)

⁸ Spatial extent over which disposed waste presents a risk to human health.

⁹ The ISAM FEP name was changed from “repository assumptions” to “facility assumptions” to avoid confusion related to terminology.

¹⁰ For example, linear relationship of human health effect to dose with no threshold dose below which no effects are observed.

Table C-8 Assessment Context, Site Characterization, or Operational Factors Considered in Developing FEPs

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	<p>Example Factors (Project IDs) BMA=BIOMASS, BMO=BIOMOVs, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
			<p>Assessment Audience (HAN 0.4.05)</p>
			<p>Regulatory Requirements and Criteria (e.g., radiological protection standards, optimization) (HAN 0.2, CLV 3)</p>
			<p>Protection of Human Health and the Environment (SRS 1.2.02)</p>
Regulatory requirements and exclusions	0.09		<p>Performance Requirements and Criteria (SRS 1.2.03)</p> <p>ALARA (SRS 1.2.05)</p>
			<p>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)</p>
			<p>Waste Acceptance Criteria (SRS 1.2.07)</p>
			<p>Uncertainties, or confidence (BMA, 2.1.2.10)</p>
			<p>Confidence, Model (e.g., calibration, verification, validation) (HAN 0.3.04, SRS 1.3.12)</p>
Model and data issues (e.g., uncertainty, model abstraction)	0.10		<p>Uncertainties, treatment of (e.g., subjective, future, conceptual, mathematical, model, parameter) (HAN 0.3.02, SRS 1.3.10)</p> <p>Sensitivity Analysis, Performance of (HAN 0.3.03, SRS 1.3.11)</p>
			<p>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)</p>
			<p>Software Codes (SRS 1.3.02)</p>
			<p>Assessment Philosophy (e.g., assessment and modeling approach, treatment of uncertainty, sensitivity analysis, and confidence building) (BMA 2.1.3, HAN 0.3)</p>
Assessment Philosophy or Approach	New		<p>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)</p>
			<p>Modeling Approach (e.g., screening, bounding, deterministic, probabilistic) (HAN 0.3.05, SRS 1.3.03)</p>
			<p>Alternative Simplified Modeling Approach (SRS 1.3.13)</p>

Table C-8 Assessment Context, Site Characterization, or Operational Factors Considered in Developing FEPs

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example Factors (Project IDs) BMA=BIOMASS, BMO=BIOMOVs, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Transparency of Assessment Approach (SRS 1.1.05)
			Documentation and Presentation of Results (SRS 1.1.04)
Site investigation	1.1.01		Technical Requirements (e.g., site characterization) (HAN 0.2.03) Investigations, Site (e.g., geology, hydrogeology, geochemistry, tectonic and seismicity, surface environment, meteorology and climatology, geography and demography, natural resources and land use) (HAN 1.1.01, CLV 82)
Schedule and planning	1.1.09		Site Characterization and Investigations (SRS 3.1.01) 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=BIOMOVES, 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)
Closure, facility ¹⁵	1.1.05		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, 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	<p>Example FEPs (Project IDs)</p> <p>BMA=BIOMASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
			<p>Closure System Features and Materials (SRS 3.3.01)</p> <p>Compaction Error (CLV 98)</p>
Waste allocation (projected inventory, waste acceptance criteria)	1.1.07		<p>Operation, Disposal Facility (e.g., waste acceptance, waste allocation) (HAN 1.1.05)</p> <p>Radionuclide inventory disposed and remaining in the disposal facility (HAN 0.4.6.11)</p> <p>Activity limits in disposed waste (HAN 0.4.6.12, SRS 4.2.02)</p> <p>Waste allocation and emplacement (SRS 4.1.04)</p> <p>Homogeneity (SRS 4.1.05)</p> <p>Waste Acceptance Criteria (SRS 1.2.07)</p> <p>Quality control (CLV 88)</p>
Quality control	1.1.08		<p>Technical Requirements (e.g., QA) (HAN 0.2.03)</p> <p>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)</p> <p>Procurement of Items and Services (quality assurance) (SRS 3.2.03)</p> <p>Manufacturing and Commissioning of Components (including defects) (SRS 3.3.02)</p> <p>Inadequate Quality Assurance/Control and Deviations from Design (SRS 3.8.04)</p>
Accidents and unplanned events ¹⁶	1.1.12		<p>Accidents and unplanned events (e.g., human-induced and naturally occurring) (HAN 1.1.09, SRS 6.4.05, CLV 99, CLV 91)</p> <p>Seismicity and effects (e.g., soil liquefaction) (HAN 1.2.03, SRS 6.2.01, CLV 50)</p>
Seismicity	1.2.03		<p>Seismicity Associated with Igneous Activity (SRS 6.2.04)</p> <p>Earthquakes (CLV 40)</p> <p>Tsunami (CLV 30)</p>

¹⁶ For example, earlier than expected engineered barrier system failure, unexpected event, or unexpected waste.

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIO MASS, BMO=BIO MOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Faulting (CLV 41)
Volcanic and magmatic activity	1.2.04	Long-term	Volcanic and magmatic activity (HAN 1.2.04, SRS 6.3.02, CLV 52) Igneous Intrusion Into the Closure Facility (SRS 6.3.01)
Hydrothermal activity	1.2.06	Long-term	Geological intrusion (CLV 43)
Erosion and sedimentation	1.2.07		Hydrothermal activity (HAN 1.2.06, SRS 5.2.02, CLV 13) Denudation and Deposition (large-scale, including erosion, corrosion, 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)
Pedogenesis ¹⁷	1.2.08		Sedimentation (SRS 2.6.06, CLV 14)
Salt diapirism and dissolution	1.2.09	Long-term	Pedogenesis (factors related to the development and origin of soils, may also effect caps) (HAN 1.2.09, SRS 2.6.05, CLV 59)
Hydrological/hydrogeological response to geological changes	1.2.10	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 (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)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIOMASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
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	1.3.05	Long-term	Glacial and ice sheet effects, local (HAN 1.3.05, CLV 34)
Warm climate effects (tropical and desert) ¹⁹	1.3.06		Warm climate effects (HAN 1.3.06, SRS 2.7.05) Hydrological/hydrogeological response to climate changes (e.g., change in driving forces of flow and flow) (HAN 1.3.07)
Hydrological/hydrogeological response	1.3.07	Long-term	Climate Driven Changes (BMO 2.1.1.2)

¹⁸ Does not include anthropogenic impacts on climate change.

¹⁹ Facilities in tropical climates may experience extreme weather patterns such as monsoons, hurricanes, flooding, storm surges, high winds etc.; arid climates may be dominated by infrequent storm events.

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIO MASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
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)
Other geomorphological changes	1.3.10		Ecological response to climate changes (e.g., soil, water, atmosphere, solar radiation, living organisms, ecological adaptation) (HAN 1.3.08, CLV 28) Geomorphologic responds to climate changes (e.g., periglacial landforms, warm climate) (HAN 1.3.10) Surface excavations (e.g., construction, remediation, geotechnical investigation, waste disposal) (HAN 1.4.07, CLV 65)
Pollution (as it impacts site performance, radionuclide mobility, or monitoring) ²⁰	1.4.07		Artificial soil fertilization (BMA 2.3.2.1.1, BMO 2.2.3.3) Chemical pollution (BMA 2.3.2.1.2, BMO 2.2.1.1) Acid rain (BMA 2.3.2.1.3, BMO 2.2.1.1.1, SRS 2.7.04) Pollution (e.g., soil, groundwater, and air that may increase mobility of radionuclides) (HAN 1.4.12, SRS 2.2.07)
Inventory, radionuclide and other material	2.1.01		Inventory, waste (e.g., waste stream, volume, homogeneity, radiological content, non-radiological content (as it impacts radionuclide mobility), classification, uncertainty) (HAN 2.1.01, SRS 4.1.03) Source Term/Radionuclide Content (BMA 2.1.6, BMO 1.2.3.1)
Wasteform materials, characteristics and degradation processes	2.1.02		Wasteform, characteristics and degradation processes (HAN 2.1.02, CLV 100) Removal or Stabilization of Waste (stabilization of waste) (SRS 3.2.07) Waste characteristics (e.g., metallic, inorganic/non-metallic, organic, volatile, combustible) (SRS 4.1.07, 4.1.08, 4.1.09, 4.1.10, CLV 77, CLV 104) Waste degradation (inorganic and organic) (SRS 4.2.06, SRS 4.2.07)
Container materials, characteristics and	2.1.03		Container materials, characteristics and degradation processes (e.g., corrosion) (HAN 2.1.03, CLV 96, CLV 97, CLV 100)

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

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	<p>Example FEPs (Project IDs)</p> <p>BMA=BIO MASS, BMO=BIO MOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
degradation processes			<p>Waste tank, container, or package characteristics (physical, chemical and mechanical properties) (SRS 3.3.04)</p> <p>Waste Container, Package, or Over-Pack Failure (e.g., corrosion, manufacturing defects, improper seal) (SRS 3.7.06)</p>
Buffer/backfill materials, characteristics and degradation processes	2.1.04		<p>Buffer/backfill, characteristics and degradation processes (HAN 2.1.04, CLV 100)</p> <p>Closure System Buffer (Closure Cap, Backfill, and Near-Field Soil) Properties (e.g., dehydration of zeolites, mineralogical hydration, geothermal fluid impacts, sorption, use of bentonite and vermiculite) (SRS 3.3.05, SRS 3.3.06)</p> <p>Swelling of Backfill and Emplacement Materials (e.g., bentonite and vermiculite degradation) (SRS 3.3.06, SRS 3.7.08)</p>
Engineered barriers system (EBS), characteristics and degradation processes	2.1.05		<p>Other engineered features, characteristics and degradation processes (e.g., final or interim covers or multi-layer cap designs) (HAN 2.1.05, CLV 100)</p> <p>Multi-Barrier Safety Function (combination of natural and engineered barriers) (SRS 3.1.04)</p> <p>Design Basis for Engineered Components (SRS 3.2.01)</p> <p>Consolidation of System Components (consolidation of engineered barrier system components that may affect the chemical environment and release) (SRS 3.3.03)</p> <p>Chemical Degradation of Engineered System Metals (SRS 3.7.01)</p> <p>Corrosion (e.g., stress corrosion cracking, hydride cracking) (SRS 3.7.02, SRS 3.7.03)</p> <p>Creep of Metallic Materials in the Engineered System (SRS 3.7.04)</p> <p>Oxygen Embrittlement of Engineered System Metals (SRS 3.7.05)</p> <p>Concrete Shrinkage/Expansion (may impact hydraulic properties) (SRS 3.7.09)</p> <p>Cementitious material degradation (e.g., sulfate and chloride attack, carbonation, (SRS 3.7.10, SRS 3.7.11)</p> <p>Seismic-Induced Damage or Changes to System Components (SRS 6.2.02)</p> <p>Frost Weathering (engineered cover degradation mechanism) (CLV 21)</p> <p>Geophysical effects on degradation (CLV 36)</p>

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	<p>Example FEPs (Project IDs)</p> <p>BMA=BIO MASS, BMO=BIO MOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
Other engineered features materials, characteristics and degradation processes	2.1.06		<p>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</p> <p>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)</p> <p>Ancillary Equipment and Piping/Transfer Lines (SRS 3.3.10)</p> <p>Degradation of Non-Metal Solids: Backfill, Rock, Grout, Cement, etc. (SRS 3.7.07)</p> <p>Polymer Degradation (SRS 3.7.12)</p> <p>Material Volume Changes (e.g., expansion may lead to cracking of materials) (SRS 3.8.07)</p> <p>Mechanical Effects at EBS Component Interfaces (e.g., mechanical and static loading) (SRS 3.8.09)</p>
Mechanical processes and conditions (in wastes and EBS)	2.1.07		<p>Effects of Subsidence (including increased infiltration) (SRS 6.2.03, CLV 8, CLV 103)</p> <p>Cave-In, Collapse, or Rockfall (SRS 6.4.04)</p> <p>Compaction Error (CLV 98)</p>
Hydraulic/hydrogeological processes and conditions (in wastes and EBS)	2.1.08		<p>Hydrological Processes and Conditions (processes affecting flow through waste and engineered features) (SRS 3.4.01, CLV 99)</p> <p>Hydrostatic Pressure on the Closure System (hydrostatic pressure (or suction) of saturated waste and engineered system components) (SRS 3.4.02)</p> <p>Condensation on Closure System Surfaces (SRS 3.4.03)</p> <p>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)</p> <p>Groundwater Flow and Movement (Near-Field) (e.g., preferential flow) (SRS 5.1.01)</p> <p>Focusing of Flow Along Preferred Flow Paths (Fingers, Weeps, Faults, Fractures, etc.) (SRS 5.1.05)</p> <p>Episodic Or Pulse Flow and Release (SRS 5.1.03)</p> <p>Water Influx at the Closure Facility (SRS 5.1.04)</p>

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	<p style="text-align: center;">Example FEPs (Project IDs)</p> <p style="text-align: center;">BMA=BIOMASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
			<p>Flow Diversion and Bypass Flow (focused flow around cap, flow through voids such as roots) (SRS 5.1.07)</p>
			<p>Film/Laminar Flow (through waste zone) (SRS 5.1.08)</p>
			<p>Perched Water (SRS 5.2.06)</p>
			<p>Contaminant Release Pathways (SRS 5.3.02, CLV 102)</p>
			<p>Multi-Phase Transport Processes (SRS 5.3.03)</p>
			<p>Fast Transport/Preferential Pathways (SRS 5.3.13, CLV 120)</p>
			<p>Flooding or drainage system failure (SRS 6.4.02)</p>
			<p>Mechanical effects (CLV 125)</p>
			<p>Chemical/geochemical-mediated processes, effects on contaminant release and migration (including dissolution, precipitation, speciation, solubility, sorption/desorption, colloids, chemical complexing agents, and re-concentration; 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)</p>
			<p>Evolving water chemistry in wastefrom, 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)</p>
<p>Chemical/geochemical processes and conditions (in wastes and EBS)</p>	<p>2.1.09</p>		<p>Chemical Effects of Waste-Rock Contact (direct contact of waste with rock due to failure of waste package) (SRS 3.5.08)</p>
			<p>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)</p>
			<p>Reaction Kinetics (non-equilibrium conditions) (SRS 3.5.11)</p>
			<p>Contaminant Release from the Waste Form and Engineered Barrier System (SRS 5.3.04, CLV 99)</p>
			<p>Long-Term Release of Radionuclides (SRS 5.3.14)</p>
			<p>Electrochemical effects (CLV 107)</p>

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=BIO MASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
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 Vitriified 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)
Lithological units, other	2.2.03		Stratigraphy and Host Lithology (including description, flow and transport effects, properties, homogeneity, and potential changes) (SRS 2.5.04)
Discontinuities, large scale (in geosphere)	2.2.04		Stratigraphy (e.g., stratigraphic record, formation) (HAN 2.2.01, CLV 119) Discontinuities, large scale (in geosphere) (e.g., faults, folds, dykes, aquifer formation, discontinuities affecting boundary conditions) (HAN 2.2.04, SRS 2.5.05, CLV 39)
Contaminant transport path characteristics (in	2.2.05		Contaminant migration path characteristics (in geosphere) (e.g., hydrogeological zones, interstitial geometry, bypass flow, fracture inflow, weathering) (HAN 2.2.05, CLV 111)

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	<p>Example FEPs (Project IDs)</p> <p>BMA=BIO MASS, BMO=BIO MOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
geosphere) (e.g., fracture flow, porous flow, fracture/matrix interactions)			<p>Unconsolidated soft zones (SRS 2.5.07)</p> <p>Fast Transport Pathways (SRS 5.3.13)</p>
Mechanical processes and conditions (in geosphere)	2.2.06		<p>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)</p> <p>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)</p>
Hydraulic/hydrogeological processes and conditions (in geosphere)	2.2.07		<p>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)</p> <p>Hydrological Regime and Water Balance (Near-Surface) (SRS 2.8.09)</p> <p>Aquifer Properties (including vadose and saturated zone thicknesses) (SRS 5.3.16, 5.3.17)</p> <p>Capillary rise (SRS 2.8.05)</p> <p>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)</p> <p>Interfaces Between Different Waters (SRS 5.2.04)</p> <p>Chemically-Induced Density Effects on Groundwater Flow (SRS 5.1.06)</p> <p>Unconsolidated soft zones (SRS 2.5.07)</p> <p>Hydrological Effects (CLV 17)</p> <p>Flooding (CLV 19)</p>
Chemical/geochemical	2.2.08		<p>Properties of the Groundwater Plume (BMO 1.2.3.2)</p>

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	<p style="text-align: center;">Example FEPs (Project IDs)</p> <p style="text-align: center;">BMA=BIO MASS, BMO=BIO MOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
processes and conditions (in geosphere)			Chemical/geochemical processes and conditions (in geosphere) (e.g., chemical composition and evolution; geochemistry factors, evolution and geochemical interactions; groundwater recharge; geothermal effects, solubility controls) (HAN 2.2.08, CLV 9)
			Evolving Water Chemistry in the Far-Field (e.g., perturbations due to climate change which can cause infiltration of sea-water or glacial melt waters) (SRS 3.5.04)
			Complexation in the Natural System (SRS 3.5.10)
Biological/biochemical processes and conditions (in geosphere)	2.2.09		Alteration and Chemical Weathering Along Flow Paths (SRS 5.1.10)
Thermal processes and conditions (in geosphere)	2.2.10		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) (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)
Gas sources and effects (in geosphere)	2.2.11		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) (e.g., effects of natural gases, gas induced groundwater flow) (HAN 2.2.11)
			Gas or brine pockets (CLV 6)
Undetected features (in geosphere) (e.g., boreholes, abandoned mines, gas or brine pockets, geological features [faults, dykes, lava tubes, breccia pipes, lava tubes])	2.2.12		Undetected features (in geosphere) (HAN 1.2.11, SRS 2.5.08)
			Breccia pipes (CLV 37)
			Lava tubes (CLV 47)
			Gas intrusion (CLV 121)

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	<p style="text-align: center;">Example FEPs (Project IDs)</p> <p style="text-align: center;">BMA=BIOMASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
Geological resources	2.2.13		<p>Geological resources (in geosphere) (e.g., methane, water, and other resources; and near-surface and deep deposit exploration) (HAN 2.2.12, CLV 119)</p> <p>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)</p> <p>Hydraulic fracturing (CLV 44)</p> <p>Resource extraction (CLV 89)</p>
Topography and morphology	2.3.01		<p>Topography and morphology (e.g., landform, changes in landform, topography changes on climate) (HAN 2.3.01, SRS 2.5.02)</p>
Soil and sediment (physical, chemical and biological properties; sedimentation; evolution)	2.3.02		<p>Chemical changes (e.g., chemical changes to soil) (BMA 2.3.1.1.2)</p> <p>Geosphere/Biosphere Interface (e.g., deep soil) (BMO 1.2.1)</p> <p>Environmental Components (e.g., top soil, deep soil) (BMO 1.3.2.3)</p> <p>Alkalinization (BMO 2.1.1.1.2.1)</p> <p>Soil conversion (BMO 2.1.1.1.3.1)</p> <p>Soil and sediment (composition, structure, profile, type, depth, and impact on contaminant mobility) (HAN 2.3.03, SRS 2.5.10)</p> <p>Radionuclide Accumulation (Recycling) in Soils (SRS 4.3.05)</p> <p>Sedimentation (CVL 14)</p>
Aquifers and water-bearing features, near surface	2.3.03		<p>Environmental Components (e.g., deep soil, biosphere aquifer) (BMO 1.3.2.3)</p> <p>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)</p>
Lakes, rivers, streams and springs	2.3.04		<p>Geosphere/Biosphere Interface (e.g., river) (BMO 1.2.1)</p> <p>Environmental Components (e.g., river water, river sediment) (BMO 1.3.2.3)</p>

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	<p style="text-align: center;">Example FEPs (Project IDs)</p> <p style="text-align: center;">BMA=BIOMASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
			<p>Terrestrial surface water bodies (lakes, dams, rivers, streams, springs, wetlands, dilution, and recharge/discharge zones) (HAN 2.3.05)</p>
			<p>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)</p>
			<p>Lake Effects (including appearance, disappearance of large lake leading to possible sedimentation, wave action, erosion/inundation, isostasy) (CLV 18, CLV 32)</p>
			<p>Wave Action (from large lake) (CLV 33)</p>
Coastal features	2.3.05		<p>Regional subsidence (effect on lake levels) (CLV 49)</p>
Marine features	2.3.06		<p>Coastal features and processes (HAN 2.3.06, CLV 26)</p>
Atmosphere (e.g., physical transport of gases, chemical and photochemical reactions, aerosols and dust)	2.3.07		<p>Marine features and effects (HAN 2.3.07, CLV 29)</p>
			<p>Environmental Components (e.g., atmosphere) (BMO 1.3.2.3)</p>
			<p>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)</p>
Vegetation	2.3.08		<p>Effects related to air and vapor flow and evaporation within the system (SRS 5.2.05)</p>
			<p>Gas Transport (CLV 117)</p>
			<p>Resuspension (CLV 23)</p>
			<p>Atmospheric dispersion (CLV 24)</p>
			<p>Tornado (CLV 25)</p>
			<p>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)</p>
Animal populations (e.g., diets, external contamination of)	2.3.09		<p>Living components of ecosystems (BMA 2.2.3.2.1)</p>
			<p>Animal populations (including animal types, burrowing animals, scavengers and predators, and pets) (HAN 2.3.10, SRS 2.4.04)</p>

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	<p>Example FEPs (Project IDs)</p> <p>BMA=BIOMASS, BMO=BIOMOVs, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
Meteorology	2.3.10		<p>Identification and Characterization of Climate Categories (BMA 2.2.1.2)</p> <p>Differentiation of Climate Categories (BMO 1.3.1.1)</p> <p>Diurnal variability (BMA 2.3.1.2.1)</p> <p>Meteorology (HAN 2.3.11, CLV 22)</p>
			<p>Precipitation (control on the amount of runoff and infiltration, flow in the unsaturated zone, and groundwater recharge) (SRS 2.7.03)</p> <p>Events (e.g., flooding, tornados, hurricanes) (CLV 10, CLV 25, CLV 27)</p> <p>Insolation (CLV 28)</p>
Hydrological regime and water balance (near surface)	2.3.11		<p>Interannual and longer timescale variability (e.g., seasonal water table fluctuations) (BMA 2.3.1.2.3)</p> <p>Hydrological regime and water balance (near-surface) (HAN 2.3.12)</p> <p>Water (characteristics of water and its evolution) (SRS 2.8.01)</p> <p>Evapotranspiration, Surface Runoff, Infiltration and recharge (SRS 2.8.03, SRS 2.8.04, SRS 2.8.06, CLV 118)</p> <p>Hydrological Effects (CLV 17)</p>
Erosion and deposition	2.3.12		<p>Physical changes (e.g., erosion, sea level change) (BMA 2.3.1.1.1, BMO 2.1.1.1.3)</p> <p>Erosion (BMA 2.3.1.4.2.10, BMO 2.1.1.1.3.2, CLV 11)</p> <p>Erosion and deposition (HAN 2.3.13)</p> <p>Erosion and weathering (SRS 2.6.08)</p> <p>Deposition (SRS 2.6.07)</p> <p>Mass Wasting (soil movement as a result of gravitational forces) (SRS 2.6.09)</p> <p>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)</p>

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=BIO MASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
			Subrosion (CLV 15)
Ecological/biological/microbial systems (e.g., features, microbial activity, chemical changes). The NEA database also has the following examples: fire, ecological succession.	2.3.13		Ecosystems (BMA 2.2.3.2) Non-living components of ecosystems (BMA 2.2.3.2.2) Interannual and longer timescale variability (e.g., natural succession after fire) (BMA 2.3.1.2.3) Burning (BMO 2.1.2.1.3) Chemical Changes Caused by Micro-Organisms (BMO 2.1.1.1.2.2) Ecological/biological/microbial systems (HAN 2.3.14) Biomes (e.g., desert, grassland, forest, and mountain biomes) (HAN 2.3.02, SRS 2.4.01) Insolation, effects of (CLV 28)
Animal/plant intrusion leading to vault/trench disruption (e.g., root uptake, burrowing animals)	2.3.14		Transport mediated by flora and fauna (e.g., root uptake, transpiration, interception, intake by fauna, bioturbation, burrowing, root development, translocation) (BMA 2.3.1.3.1, BMO 2.1.2.7, CLV 109) Animal/Plant intrusion (HAN 2.3.15, SRS 6.1.05)
Radioactive decay and in-growth	3.1.01		Radioactive decay and in-growth (HAN 3.1.01, SRS 4.2.01, CLV 60) Radionuclide properties, other (HAN 3.1.02)
Chemical/organic toxin stability	3.1.02		Chemical/organic toxin stability (HAN 3.1.04)
Inorganic solids/solutes	3.1.03		Inorganic solids/solutes (HAN 3.1.05)
Volatiles and potential for volatility	3.1.04		Volatiles and potential for volatility (HAN 3.1.06)
Organics and potential for organic forms	3.1.05		Organics and potential for organic forms (HAN 3.1.03)
Noble gases	3.1.06		Noble gases (HAN 3.1.07)
Dissolution, precipitation	3.2.01		Release Mechanisms (BMA 2, 1.6.2, CLV 102)

Table C-9 Generic FEPs List for Near-Surface Disposal in the United States (FEPs independent of human action and exposure assumptions)

IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs)
and crystallisation, contaminant			<p>BMA=BBIOMASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p> <p>Source Term Mechanisms (BMA 2.1.6.3)</p> <p>Dissolution/precipitation (BMA 2.3.1.4.4.1, BMO 2.1.3.1.1, SRS 4.3.02)</p> <p>Chemical/geochemical-mediated processes, effects on contaminant release and migration (e.g., dissolution, precipitation, and crystallisation) (HAN 3.2.02)</p> <p>Dissolution (CLV 115)</p>
Speciation and solubility, contaminant	3.2.02		<p>Source Term/Release Mechanisms (BMA 2.1.6.2, BMA 2.1.6.3, CLV 102)</p> <p>Chemical/geochemical-mediated processes, effects on contaminant release and migration (e.g., speciation and solubility) (HAN 3.2.02, CLV 9)</p> <p>Contaminant Solubility, Solubility Limits, and Speciation (SRS 4.2.03)</p> <p>Reduction-Oxidation Potential (Redox Fronts) (SRS 4.2.04)</p> <p>Solubility and Sorption Changes From Chemical and Temperature Interactions (SRS 4.3.03)</p> <p>Source Term/Release Mechanisms (BMA 2.1.6.2, BMA 2.1.6.3, CLV 102)</p> <p>Adsorption/desorption (BMA 2.3.1.4.4.2, BMO 2.1.3.1.2, SRS 5.3.11, CLV 111)</p> <p>Soil and sediment (e.g., sorptive capability) (HAN 2.3.08)</p> <p>Chemical/geochemical-mediated processes, effects on contaminant release and migration (e.g., sorption/desorption processes) (HAN 3.2.02, CLV 9)</p> <p>Electrochemical Effects in the Closure System (Including Anion Exclusion) (SRS 3.8.08)</p> <p>Solubility and Sorption Changes From Chemical and Temperature Interactions (SRS 4.3.03)</p> <p>Radionuclide Interaction with Corrosion Products (SRS 4.5.03)</p> <p>Colloid formation (BMA 2.3.1.4.4.3)</p> <p>Transport of Colloids (BMO 2.1.2.3.6.2)</p> <p>Colloids mediated migration of contaminant (HAN 3.2.10, CLV 110)</p>
Sorption/desorption processes, contaminant	3.2.03		
Colloids, contaminant interactions and transport with	3.2.04		

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IAEA ISAM FEP List	IAEA ISAM ID	Long-Term	Example FEPs (Project IDs) BMA=BIO MASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
Chemical/complexing agents, effects on contaminant speciation/transport	3.2.05		Source Term Content of Other Hazardous Materials ²¹ (BMO 1.2.3.3)
Microbial/biological/plant-mediated processes, contaminant	3.2.06		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)
Water-mediated transport of contaminants	3.2.07		Microbial/biological-mediated processes, effects on contaminant release and migration (HAN 3.2.03, SRS 2.4.02, CLV 54, CLV 102) 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)
Solid-mediated transport of contaminants	3.2.08		Porous Media Aqueous Transport Processes (e.g., infiltration, percolation, matrix diffusion, diffusion/dispersion, dual flow systems, capillary rise, groundwater transport) (BMO 2.1.2.3, CLV 118) Physical Processes (e.g., rainfall, snowfall, evaporation, evapotranspiration) (BMO, 2.1.3.2) Surface Water Aqueous Transport Processes (e.g., surface water run-off, transport in water bodies) (BMO 2.1.2.2, CLV 17, CLV 111) Water-mediated migration of contaminants (including groundwater advection, dispersion, dilution, imbibition, diffusion, multi-phase, unsaturated flow; surface water transport; currents; and sea spray) (HAN 3.2.04, SRS 5.3.07, SRS 5.3.08, SRS 5.3.09, CLV 16, CLV 112, 113, 114) Dilution of Radionuclides in Groundwater (SRS 4.3.04) Contaminant Release Pathways (water-mediated release from infiltration, breach of engineered barriers or wasteform, and leaching) (HAN 3.2.01, CLV 118, CLV 119) Leaching (SRS 3.5.14)

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	<p style="text-align: center;">Example FEPs (Project IDs)</p> <p style="text-align: center;">BMA=BIO MASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
			<p>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)</p> <p>Contaminant Release Pathways (e.g., solid-mediated release from intrusion, natural disruption, or animal action) (HAN 3.2.01, CLV 102)</p>
			<p>Solid-Mediated Migration of Contaminants (SRS 5.3.05)</p> <p>Gaseous Release (BMO 1.2.2.2)</p> <p>Gaseous Transport (BMO 2.1.2.1.1.)</p>
Gas-mediated transport of contaminants	3.2.09		<p>Gas-mediated migration of contaminants (including expelling groundwater, gas-phase transport, and multi-phase flow effects) (HAN 3.2.06)</p> <p>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)</p>
Atmospheric transport of contaminants	3.2.10		<p>Gas-Mediated Migration of Contaminants (SRS 5.3.06)</p> <p>Atmospheric transport (e.g., gas, aerosols, evaporation, wet/dry deposition) (BMA 2.3.1.4.1)</p> <p>Aerosol Transport (BMO 2.1.2.1.2)</p> <p>Wet Deposition (BMO 2.1.2.5.4.5)</p> <p>Atmospheric migration of contaminants (including convection, diffusion, turbulence, deposition, saltation, burning, showers and humidifiers) (HAN 3.2.07, CLV 111)</p> <p>Dust devils (CLV 116)</p>
Animal, plant and microbe mediated transport of contaminants (e.g., microbial-enhanced contaminant transport)	3.2.11		<p>Recycling of bulk solid materials (e.g., recycling materials for compost or mulch) (BMA 2.3.2.3.5, BMO 2.2.3)</p> <p>Fodder products (BMA 2.4.1.1.3)</p> <p>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)</p>

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)
Radiological toxicity/effects	3.3.06		BMA=BIOMASS, BMO=BIOMOVs, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
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=BIOMOVES, 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 inadvertent 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	<p>Example FEPs (Project IDs)</p> <p>BMA=BIOMASS, BMO=BIOMOVES, CLV=Clive, HAN=Hanford, SRS=Savannah River Site</p>
			<p>Igneous or Seismic Event Precedes Human Intrusion (making it difficult to recognize engineered wasteform) (SRS 6.1.06)</p>
Drilling activities (human intrusion)	1.4.03		<p>Water extraction by pumping (BMA 2.3.2.2.2, BMO 2.2.4.1)</p> <p>Water recharge by pumping (BMA 2.3.2.2.3)</p>
Mining and other underground activities (human intrusion)	1.4.04		<p>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)</p> <p>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)</p>
Un-intrusive site investigation	1.4.05		<p>Un-intrusive site investigation (HAN 1.4.06)</p>
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)
Archaeology	1.4.09		<p>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)</p> <p>Community development (e.g., establishment of residences) (CLV 64, CLV 70)</p> <p>Land use (CLV 72)</p> <p>Archaeology (HAN 1.4.09)</p>
Water management	1.4.10		<p>Well supply (BMA 2.3.2.3.2, BMO 2.2.4.1.1)</p>

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=BIO MASS, BMO=BIO MOVS, CLV=Clive, HAN=Hanford, SRS=Savannah River Site
(wells, reservoirs, dams)			Dam building (BMA 2.3.2.2.4) Other water supply (BMA 2.3.2.3.3) Irrigation (BMA 2.3.2.3.4, BMO 2.2.3.1.2, CLV 83) Geosphere/Biosphere Interface (e.g., biosphere aquifer with well) (BMO 1.2.1) Environmental Components (e.g., well) (BMO 1.3.2.3) Water management (including construction of dams, reservoirs, canals, pipelines; and potential for flooding) (HAN 1.4.10, SRS 2.2.02, CLV 94) Flooding or drainage system failure (SRS 6.4.02)
Social and institutional developments ²⁶	1.4.11		Loss/degradation of societal memory (HAN 1.4.02.06)
Technological developments ²⁷	1.4.12		Loss of archives/records (HAN 1.4.02.07) Social and Institutional Developments (loss of records or society memory) (SRS 2.3.03)
Remedial actions	1.4.13		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 (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

ADDITIONAL APPROACHES TO CONSTRUCT SCENARIOS AND CONCEPTUAL MODELS

This appendix presents techniques for constructing scenarios and conceptual models. Many of the techniques discussed may be from non-LLW examples (NEA, 1992; IAEA, 2004; NRC, 1995; SKB, 2008); however, the NRC staff believes the techniques and associated references could be of value to a licensee who is looking for possible approaches to construct alternative scenarios and alternate conceptual models. Licensees have the flexibility to use any documentable technique and are not required to use the techniques presented in this appendix.

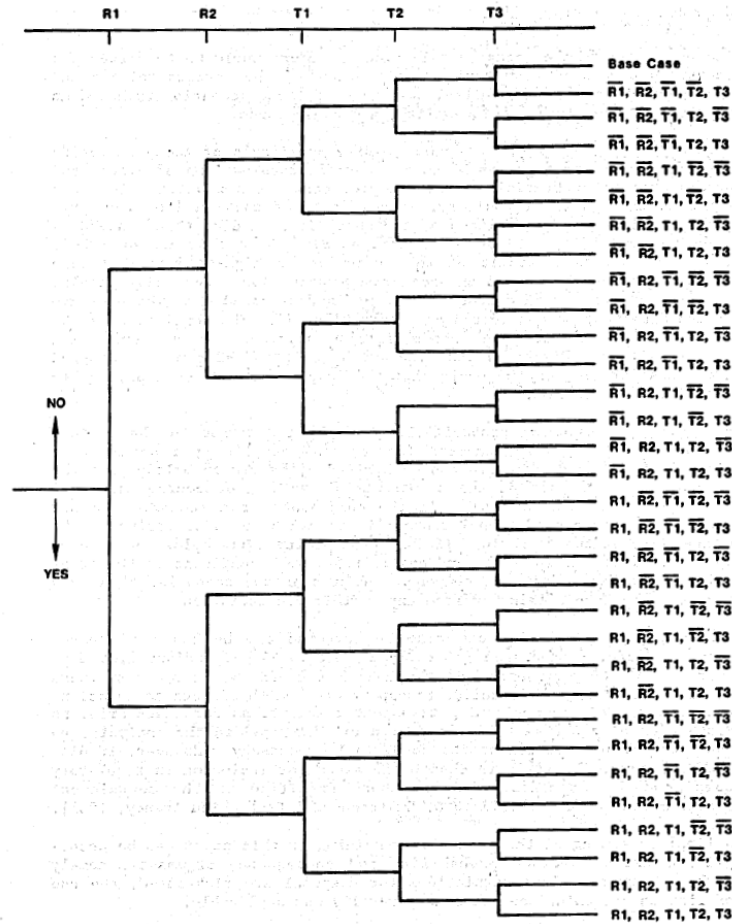
The techniques presented here can provide a logical structure for the comprehensive documentation of the relevant processes and their representation in models or scenarios. The techniques are not mutually exclusive and may be used in combination. Whatever techniques are used, the judgment of performance assessment modelers and scientific subject experts is important to successfully completing this portion of the performance assessment (PA) process.

Event tree analyses

Event trees are one of the oldest techniques used to assess the operational safety of nuclear reactors. Probabilities can be systematically treated but the variations are mainly binary, (fault - no fault). This method describes system behavior as an event or series of events leading to system failure or loss of function. Application of the technique yields a number of combinations of basic events whose occurrence causes system failure or loss of function. These event combinations are then evaluated by various screening techniques to determine high risk scenarios. This technique is not used extensively in the context of radioactive waste disposal for several reasons including: (1) most processes are generally slow and difficult to define as abrupt events, and (2) the tree methods are not suitable to handle interaction and feedback between features, events, and processes (FEPs). In addition, the sheer number of possible combinations in an event tree can very rapidly become unmanageable.

Logic diagrams

Another technique to assist in scenario development involves the use of logic diagrams. The development of scenarios by taking combinations of the various release and transport phenomena is illustrated by the following example in Figure D-1 (NRC, 1990). Two release phenomena (R1, R2) and three transport phenomena (T1, T2, T3) create 32 possible combinations or scenarios. The use of a logic diagram, as illustrated in Figure D-1, ensures that all possible combinations of these phenomena are identified. The central scenario represents the initial conceptualization of the disposal system. All components of the engineered barrier system are assumed to perform as designed. The other scenarios are perturbations to these central conditions (e.g., assuming less than 100 percent barrier performance).



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3 **Figure D-1 Potential combinations of two release and three transport phenomena**
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5 In another example, alternative scenarios were characterized as discrete events (NRC, 2007).
 6 Climate change, floods, and introduction of irrigated agriculture are examples of discrete events
 7 affecting the hydrologic conditions at a site. These events are often not mutually exclusive (e.g.,
 8 the occurrence of irrigated agriculture does not preclude the occurrence of climate change). By
 9 defining scenarios as possible combinations of alternative events, the scenarios can be made
 10 mutually exclusive. An example for three events is shown in Figure D-2. A “1” in the figure
 11 signifies the occurrence of the event in a scenario and a “0” indicates the absence of that event.
 12 Scenario 1 in Figure D-2 has none of the events occurring and might be referred to as a central
 13 scenario, perhaps characterized by the continuation of current hydrologic conditions into the
 14 future. For n events, this procedure will result in 2ⁿ scenarios; some of these scenarios may be
 15 discarded because of an insignificant probability or because they are not of regulatory concern.
 16 Scenario development for LLW disposal is typically qualitative; exact probability values for
 17 events characterizing scenarios will usually not be available. Qualitative science-based
 18 appraisals, such as large, medium, and small, are workable substitutes. Numerical equivalents
 19 for high, medium, and low (e.g., 0.75, 0.5, and 0.25, respectively) could be used to derive
 20 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
	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
					Scenario Probability

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.

1 **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

2
3 IAEA (2004) describes this method in more detail (also see Figure D-3). The first step of the
4 procedure of constructing an interaction matrix is to identify and define its diagonal elements.
5 This is done by exploring how the state of the system can be described in terms of physical
6 components and spatial and temporal extension of the system. Usually, the diagonal elements
7 represent system state variables (such as chemical composition of water or rock stress) and the
8 off-diagonal elements represent processes affecting the state. For example, a typical diagonal
9 element could be “groundwater composition,” which in turn can be divided into concentrations of
10 various constituents, colloid content, and other components.

11
12 As the diagonal elements of the matrix are filled in with features or components, the interactions
13 between them are identified and introduced into the appropriate off-diagonal elements of the
14 matrix. All interactions should be binary (i.e. they should be direct interactions between
15 variables in two diagonal elements and not a path via a variable in a third diagonal element).
16 For interactions described in off-diagonal elements, the variable in the diagonal element on the
17 row should affect the variable in the diagonal element on the column. Each off-diagonal
18 element should be checked for interactions, and where no interaction is found marked “none.”

19
20 In the process of identifying interaction, plausible interacting mechanisms are first considered
21 without making any evaluation of the probability of occurrence or the significance of the effect.
22 Only fully irrelevant or totally unreasonable interactions should be discarded. For each off-
23 diagonal element the question is asked whether there are any potential events or processes that
24 are affecting any of the variables assigned to the target diagonal element (found on the column)
25 and at the same time are affected by any of the variables in the source diagonal element (found
26 on the row). If the answer was yes, a short description of the interaction should be documented
27 together with the variables in the two diagonal elements that are involved in the interaction.

28
29 In addition to the interaction matrix example, IAEA (2004) also contains Appendix B, titled
30 “Generation of Scenarios for Near Surface Disposal Systems”.

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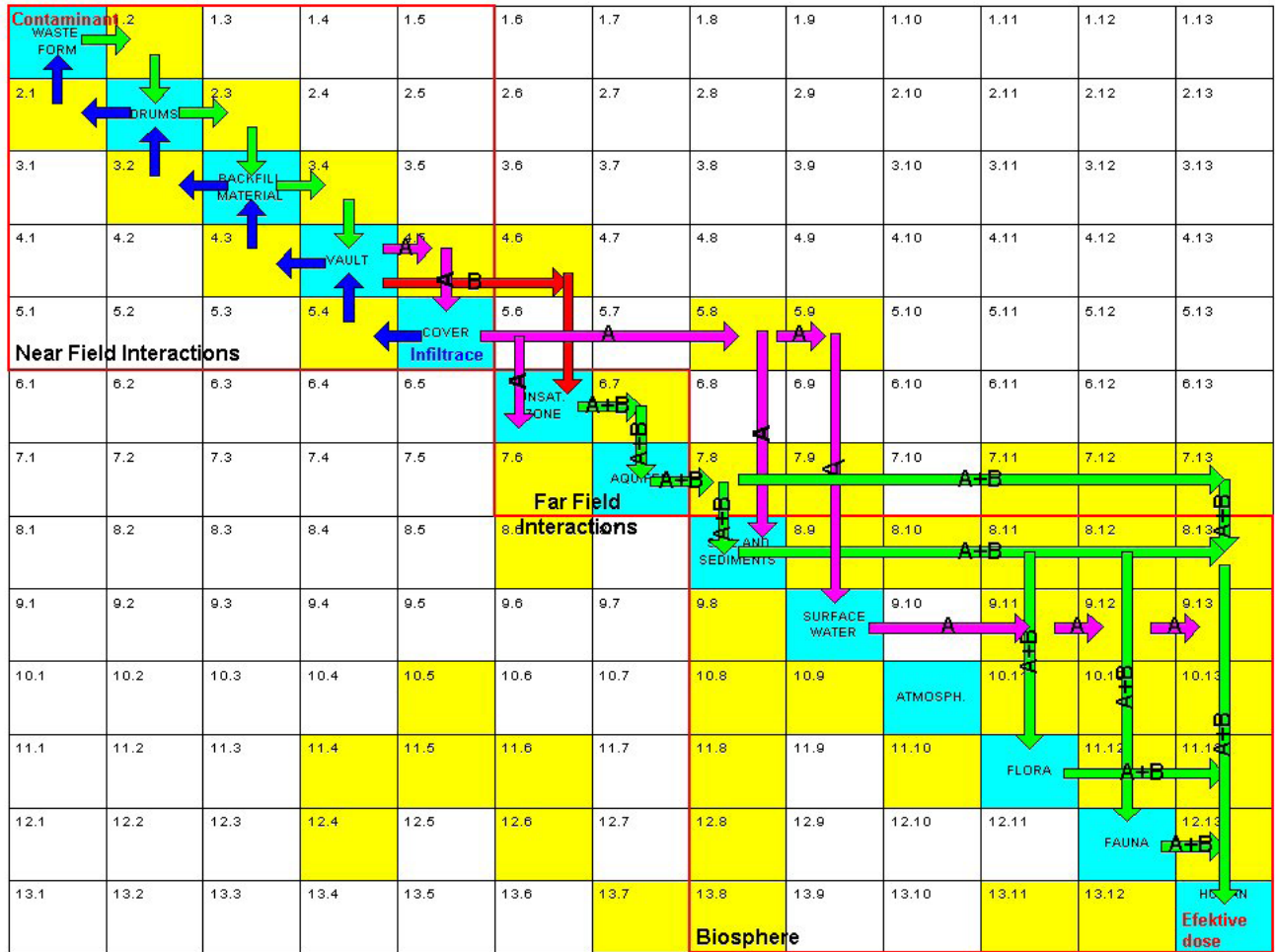


Figure D-3 Example of an interaction matrix for a central scenario including the bathtub effect (IAEA, 2004)

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 all FEPs interactions and combinations that can influence the performance of the disposal system. Each process is dealt with in detail and described as an influence between features or parameters (nodes) in the system. As the number of nodes quickly rises, these influence diagrams tend to become complicated, but are usually still helpful.

In the influence diagram approach, the direction of the influence or the interactions between FEPs is shown by the use of arrows: one arrow per direct influence and one box per FEP. An example influence diagram is given by Chapman et al. (1995) for the deep repository performance assessment project in Sweden (see Figure D-4).

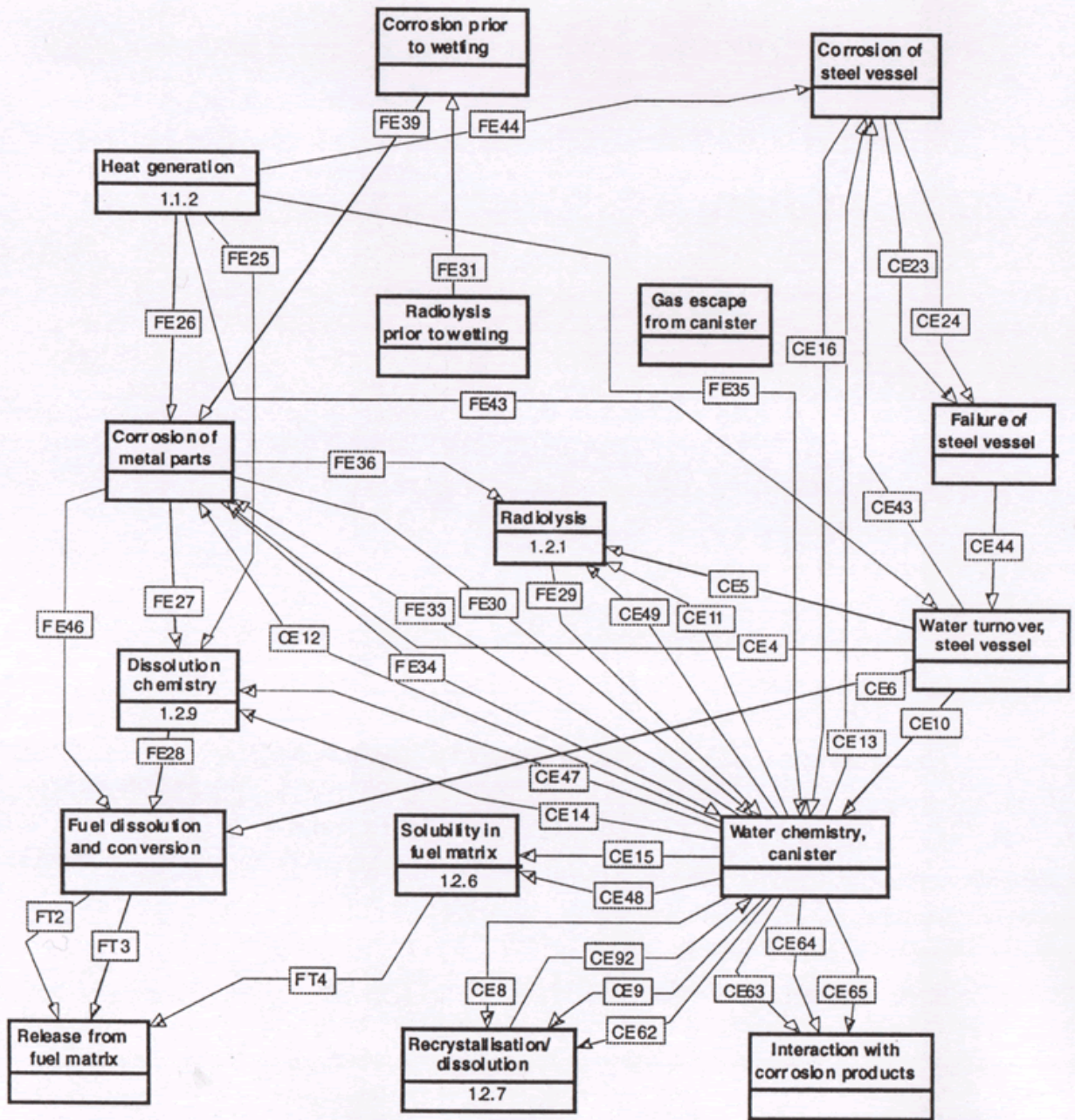


Figure D-4 Example of an influence diagram for proposed repository PA in Sweden. Many of the specific phenomena reflected in this diagram are not expected be relevant to LLW (Chapman et al., 1995)

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1 The main steps to building the influence diagram can be summarized as follows (IAEA, 2004):
2

- 3 • Definition of the system barriers and selection of FEPs relevant to the defined system.
4 The FEPs can be sorted into FEPs belonging to the system and those external scenario
5 initiating FEPs to the system.
- 6 • Representation of the system FEPs in boxes. If a FEP is relevant for several disposal
7 components, then it should be represented by one box for each of the disposal
8 components.
- 9 • Identification and representation of the influences between selected FEPs. Each
10 influence in the diagram is marked with a unique code. There are no restrictions on the
11 number of influences between two FEPs.
- 12 • Documentation of FEPs and influences. A more comprehensive description of each
13 FEP and influence is needed to clarify the representation.
14

15 The influence diagram should not include large disruptive events that would alter the system
16 features since this would produce a separate, alternative scenario and would require a separate
17 conceptual model of its own. For the influence diagram approach, process to process
18 influences should be avoided, since it is assumed that the processes do not influence each
19 other directly. Influences of this type should be broken in feature-process or process-feature
20 influences. The development of influence diagrams is an iterative process. Two FEPs may be
21 combined into one and one FEP may be split into several FEPs in order to obtain an improved
22 representation of the system. New influences between FEPs can be identified and classified
23 using a significance scale. This can be used to build a reduced influence diagram by removing
24 the influences with a lower significance than a defined level. Thereafter, various influence
25 diagrams can be developed based on the significance of the FEPs.
26

27 **Judgmental approaches**

28

29 Scenario formation can be made in several ways and human judgment is an important element
30 of scenario formation. After systematic screening, the number of retained FEPs is normally too
31 large to allow any detailed consideration of all possible combinations of them. There are,
32 however, scenario formation procedures that allow the judgment and knowledge of qualified
33 specialists to be integrated with quantitative considerations so that they result in a manageable
34 number of representative scenarios.
35

36 In the judgmental method, the assessment team or invited experts select the phenomena or
37 conditions that they believe are most important, and define possible release situations. A list of
38 phenomena or FEPs can be used as a starting point. Documentation and transparency should
39 not be lacking for the sake of expediency; formal and rigorous scenario development
40 procedures are encouraged. Documents of this procedure should be sufficiently detailed to
41 withstand detailed scrutiny by the regulatory authorities and public. Comprehensiveness and
42 traceability in both the assessment and documentation is very important when using a
43 judgmental approach.
44

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1 **APPENDIX E**
2 **SITE STABILITY ASSESSMENT EXAMPLES**
3

4 As discussed in Section 5.0, a licensee may use a design-based, model-based, or a combined
5 approach to site stability assessment. The combined approach incorporates elements of both
6 the design-based approach and the model-based approach. The licensee may use modeling to
7 assess and improve a design. In addition, they can use a risk-based approach to the site
8 stability assessment; if modeling demonstrates that the risks are not acceptable, the licensee
9 can modify the disposal site design to mitigate the risk.

10
11 The NRC staff selected the West Valley Demonstration Project (WVDP) site in this appendix as
12 an example of a model-based approach because it is presently the only example of using
13 landform evolution modeling to evaluate site stability in an NRC-regulated or NRC-reviewed
14 waste disposal or site decommissioning application. By use of the WVDP site example, the
15 NRC is not approving the approach. The Department of Energy (DOE) has not yet completed
16 its work, nor has it selected its approach to the final decommissioning of the WVDP site.
17 However, the NRC staff believes much of the content (modeling, data collection, development of
18 analogs) for the WVDP site is reasonably representative of what may be expected for a LLW
19 disposal facility, and therefore, may be useful to a 10 CFR Part 61 licensee.

20
21 This appendix also provides an example of a design-based approach from the Moab, UT
22 uranium mill tailings disposal site. A licensee of a LLW disposal facility can use the selected
23 examples to develop an understanding of the type of information and actions involved in using
24 the different approaches. A licensee should not use the information in these examples to justify
25 site-specific stability assessments for LLW disposal.
26

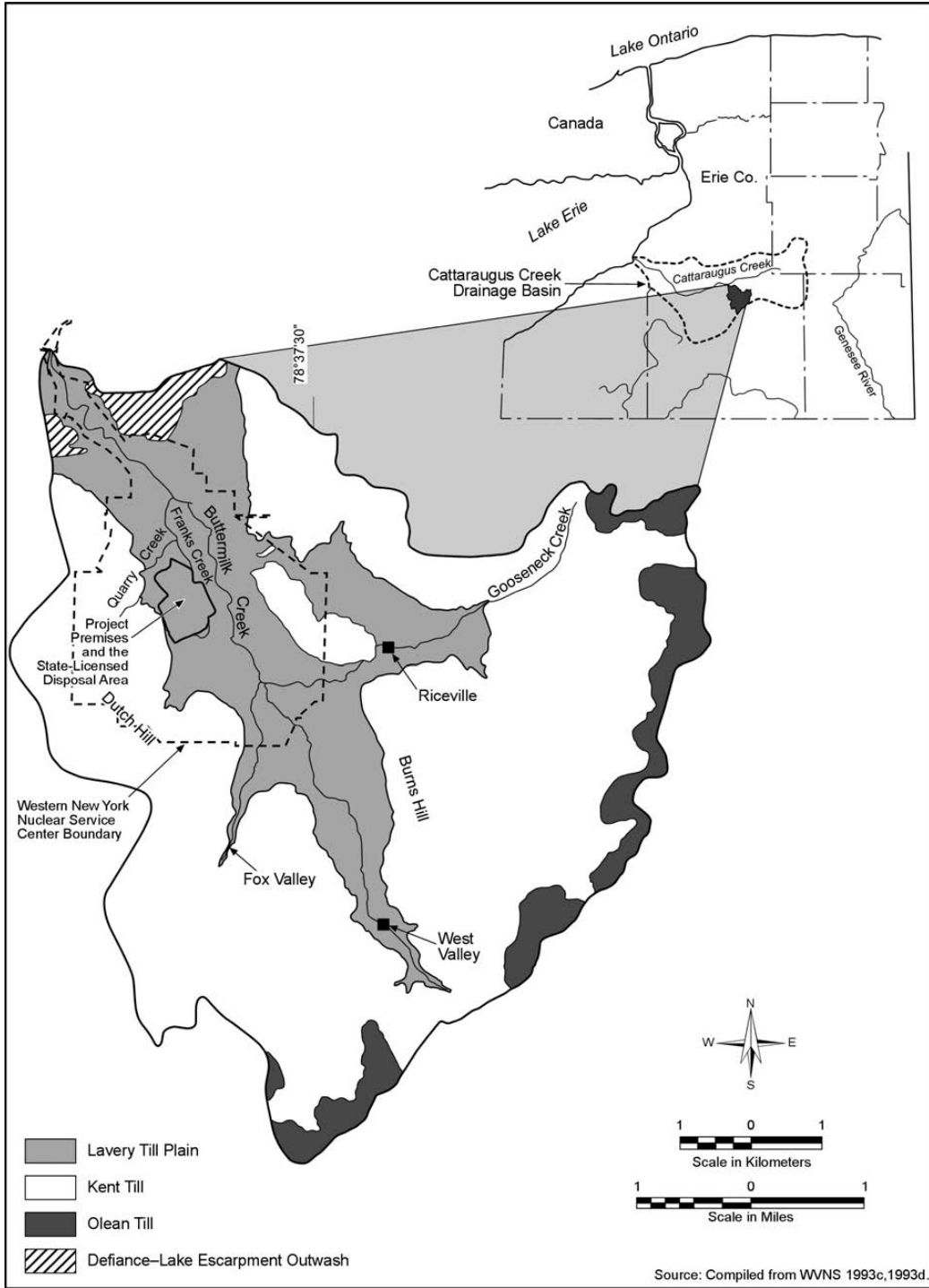
1 **Model-Based Approach: West Valley Erosion Modeling**

2 **3 Background**

4
5 West Valley is a complex decommissioning site located in western New York State, about 50
6 km (30 miles) south of Buffalo (see Figure E-1). The New York State Energy Research and
7 Development Authority (NYSERDA) holds the license and title to the 3300 acre (13.5 km²)
8 Western New York Nuclear Service Center (WNYNSC), originally developed as the first and
9 only commercial spent fuel reprocessing plant to operate in the United States. The 1980 West
10 Valley Demonstration Project (WVDP) Act gave the United States Department of Energy (DOE)
11 exclusive possession of a 200-acre portion of the larger WNYNSC which includes the former
12 reprocessing facility, a land disposal facility, and HLW tanks to allow DOE to carry out a number
13 of activities, most notably, the solidification of high-level waste that had been generated as a
14 result of spent fuel reprocessing. This 200-acre portion of the WNYNSC is referred to as the
15 WVDP, or project premises. In conjunction with NYSERDA, DOE issued a draft environmental
16 impact statement (DEIS) in 2008 evaluating various alternatives to decommissioning and long-
17 term stewardship. DOE and NYSERDA selected the Phased Decision-making alternative as
18 the preferred alternative in the final environmental impact statement (FEIS) issued in 2010
19 (DOE, 2010). Under the Phased Decision-making alternative, decommissioning would proceed
20 in two phases. Phase 1 involves near-term decommissioning work (e.g., removal of the main
21 plant process building and contaminated subsurface soils) and studies that could facilitate future
22 decision-making for the remaining facilities and areas (see Figure E-1). A phased approach
23 would allow additional time for technical and programmatic uncertainties to be addressed prior
24 to making a final decision regarding decommissioning of the site. Consistent with the Phase
25 Decision-making alternative, DOE finalized the Phase 1 Decommissioning Plan for West Valley
26 in 2009 (DOE, 2009). NRC reviewed the plan and found it to be generally acceptable (NRC,
27 2010).

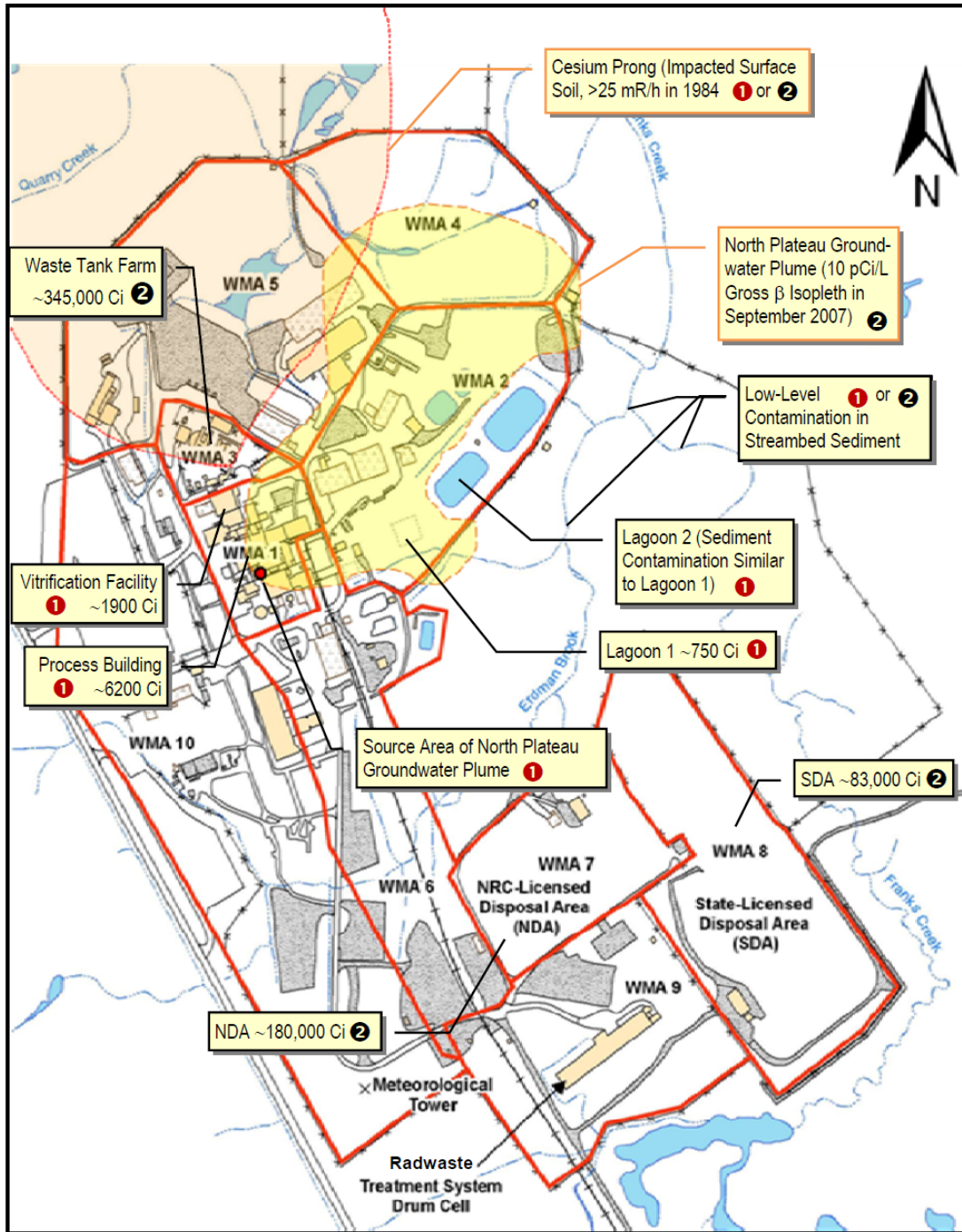
28 **29 Decommissioning Site Characteristics**

30
31 WVDP is located on the west shoulder of a steep-sided, glacially-scoured bedrock valley that is
32 filled with a sequence of glacial sediments. These glacial deposits are comprised primarily of
33 clays and silts separated by coarser-grained layers created during periods of glacial retreat.
34 The site is bordered by two streams, Franks Creek to the east and Quarry Creek to the north.
35 The WVDP is bisected by Erdmann Brook that divides the site into the North Plateau and South
36 Plateau. Franks Creek is a tributary of Buttermilk Creek. Figure E-2 below shows major site
37 facilities and features, as well as source areas to be addressed in Phase 1 and 2
38 decommissioning. Figure E-3 below shows site streams and a portion of the Buttermilk Creek
39 watershed.



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



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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)

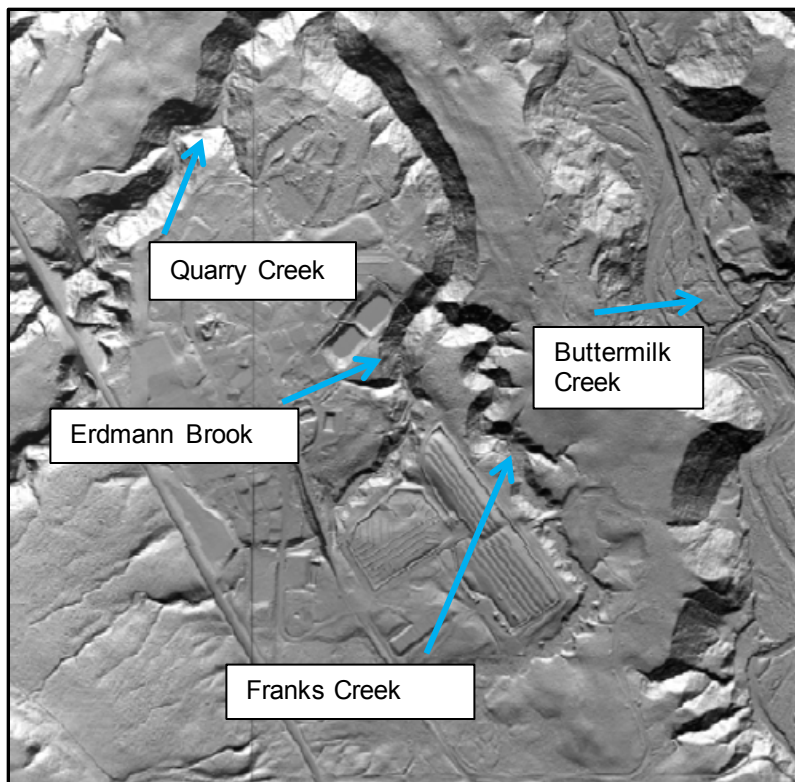


Figure E-3 West Valley Site Streams and Buttermilk Creek

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

1 release of residual radioactivity to the environment. Phase 1 studies are proposed to address
2 these technical uncertainties as described below.

3
4
5

Key Site Stability Technical Issue: Erosion

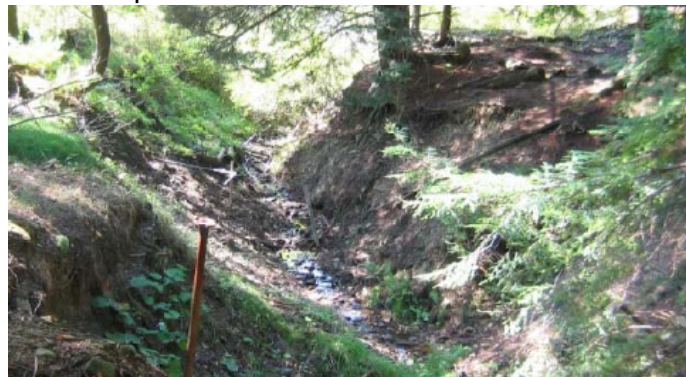
6 As stated above, erosion is a key technical issue affecting West Valley site stability. Major
7 erosion processes affecting WNYNSC, including the WVDP, include stream channel
8 downcutting, stream valley rim widening, gully advance, and in disturbed areas, sheet and rill
9 erosion. Figure E-4 shows site erosion features, while Figure E-5 shows larger Buttermilk
10 Creek watershed erosion features. Development of the current topography and stream
11 drainage patterns began with the glaciation and retreat process that ended approximately
12 17,000 years ago. Erosion processes have affected site topography due to gravitational forces
13 and water flow within the Buttermilk Creek watershed. Buttermilk Creek flows in a northwesterly
14 direction along the central axis of the WNYNSC at an elevation of approximately 60 meters
15 below the plateau on which the WVDP is located (see Figure E-1 and E-3). At WVDP, Franks
16 Creek flows along the eastern boundary and drains to Buttermilk Creek. Franks Creek
17 downcutting rates reflect base level lowering of Buttermilk Creek at the confluence of Franks
18 Creek and Buttermilk Creek. Buttermilk Creek downcutting rates are, in turn, affected by base
19 level lowering of Cattaraugus Creek at the confluence of Buttermilk and Cattaraugus Creeks.
20



Erdmann Brook Knickpoint



Franks Creek Knickpoint



WVDP Site Gully

21 **Figure E-4 WVDP Erosion Features**
22



Buttermilk Creek Landslide

1 **Figure E-5 Buttermilk Creek Watershed Erosion Features**

2
3 The FEIS (DOE, 2010) includes Channel Hillslope Integrated Landscape Development (CHILD)
4 long-term erosion modeling predictions used to evaluate the impact of erosion on site
5 performance and the ability of various alternative end states to meet decommissioning criteria.
6 The FEIS also provides details regarding the results of numerous other studies (e.g., erosion
7 frame measurements, age dating of terraces to estimate stream down-cutting and stream valley
8 rim-widening rates, aerial photography comparisons to estimate gully migration, and various
9 short-term modeling exercises) that also help to evaluate the reasonableness of CHILD
10 modeling predictions. However, the CHILD model was not used in earlier EIS analyses. Years
11 of erosion work culminated in the selection of CHILD as the primary tool used by DOE in the
12 FEIS and recommended by a DOE and NYSERDA-convened erosion working group (EWG)
13 that made recommendations for Phase 1 studies to address the long-term effects of erosion at
14 the site. The WVDP EWG indicated that CHILD is “the current state-of-the-art of predictive
15 numerical landscape evolution models and embodies significant advantages and refinements
16 compared with other generally-accepted numerical models” (2012a).

17
18 **West Valley CHILD Model**

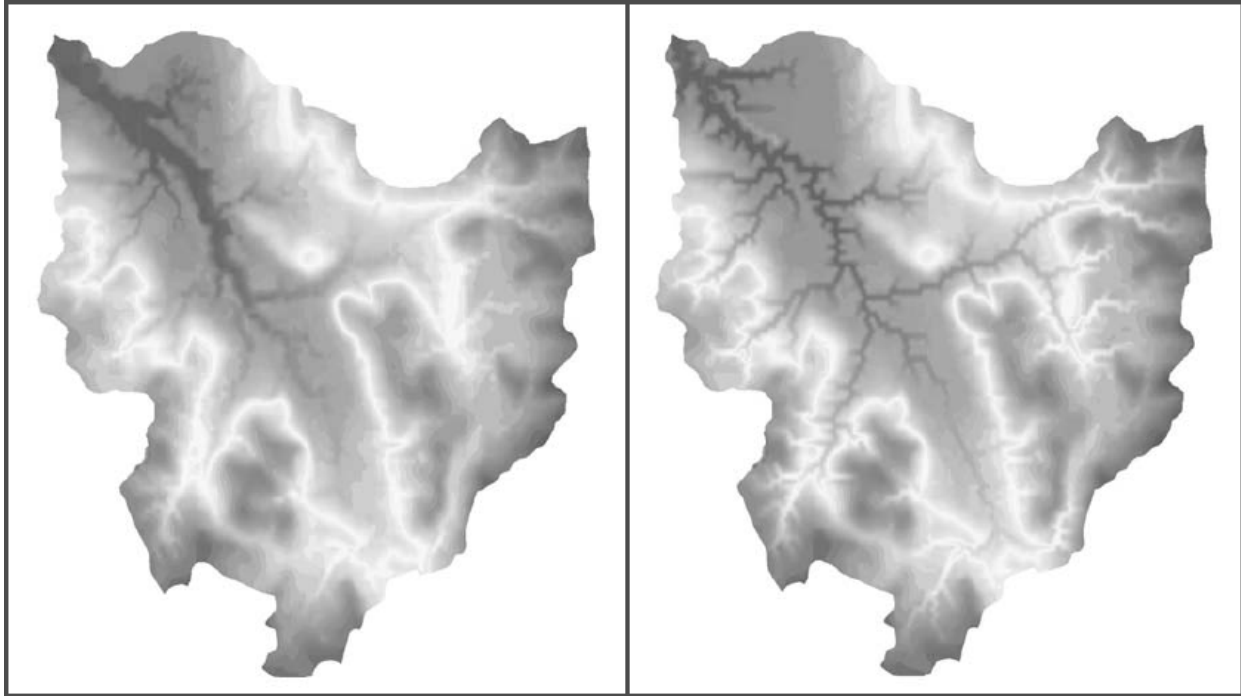
19
20 The FEIS CHILD model domain consists of the Buttermilk Creek watershed area (see Figure
21 E-6). Prior to predictive modeling, the CHILD model was calibrated against site data.
22 Calibration modeling simulations begin approximately 17,000 years in the past using remnant
23 terrace elevations and valley slope data to estimate the post-glacial (pre-incised) Buttermilk
24 Creek watershed surface. To minimize the “butterfly effect” in which small perturbations in the
25 initial conditions lead to notable differences in simulated drainage patterns, the existing drainage
26 network was etched on the initial topography. Boundary conditions included the elevation
27 history of Cattaraugus Valley at the outlet of Buttermilk Creek. As a modeling simplification, and
28 in the absence of more detailed information about climate variation over the past 17,000 years,
29 a constant climate was assumed. Three primary material types were selected including (i)
30 Paleozoic bedrock, (ii) thick but unlithified glacial sediments, and (iii) shallow surface
31 soils/sediments. Five discrete values that reflect the range of each parameter value were
32

1 assigned based on site-specific measurements (e.g., water balance data), site-specific material
2 correlations (e.g., detachment capacity related parameters), values taken from the literature for
3 similar or analog sites (e.g., creep coefficients), or commonly accepted values (e.g., critical
4 slope parameter). Selected calibration metrics reflect characteristics of the present-day
5 Buttermilk Creek watershed including the (i) creek longitudinal profile, (ii) hypsometric curve
6 (area below a certain elevation), (iii) slope-area diagram (gradient versus upstream contributing
7 areas), (iv) width function (frequency distribution of catchment flow-path length), (v) cumulative
8 area distribution (rate of flow aggregation), and (vi) strath terrace positions (pass/fail terrace
9 elevation criterion considering measurement uncertainty).

10
11 Monte Carlo methods were used in the calibration process. One thousand sets of parameter
12 values were generated by sampling the discrete parameter distributions. These 1000 sets of
13 parameter values were run through the Buttermilk Creek watershed model described above.
14 The results of 1000 simulations were evaluated against the calibration metrics. The scores for
15 the first five calibration metrics were normalized to allow equal weighting of each calibration
16 metric for subsequent averaging. Four final calibration criteria were established to select the
17 most likely sets of parameters to be used in forward modeling projections: (i) the total average,
18 normalized score must be greater than 0.5 (considering the first five calibration metrics listed
19 above), (ii) the longitudinal profile score, by itself, must be greater than 0.7, (iii) the intermediate
20 strath terrace elevation metrics should be met within a given tolerance and within a given time
21 span, and (iv) visual agreement between the model simulation results and the current
22 topography should be achieved. Only 5 runs passed the final four calibration criteria with the 5
23 sets of parameter values subsequently used in forward modeling projections to predict future
24 erosion at WVDP.

25
26 The observed topography and “best-fit” model run topography are presented in Figure E-6.
27 Sensitivity runs were also conducted that considered (i) wetter climates and less permeable
28 soils, and (ii) wetter climate parameters with fast creep (for the South Plateau only). For the
29 forward modeling projections, a digital elevation model of the current topography with a 10 m
30 resolution was used. Additionally, a second set of model simulations were run to estimate
31 erosion for the Sitewide-Close-In-Place alternative in which three burial mounds would remain
32 on the North and South Plateaus. The modeling grid was refined in the area of the North
33 Plateau and South Plateau with a grid resolution of approximately 3 m to facilitate simulation of
34 smaller scale erosion features such as gullies. Due to the computation demands of a finer grid
35 resolution, only one of the plateaus at the finer grid resolution could be modeled at a time,
36 leading two separate models reflecting the mesh refinements on the North and South Plateau.
37 With respect to boundary conditions, the final base level lowering rate from the corresponding
38 calibration run was applied at the outlet of Buttermilk Creek. The results of the 26 modeling
39 simulations were presented and discussed in the FEIS. The FEIS modeling results provided a
40 reasonable approach to evaluating erosion impacts at the WVDP. However, DOE and
41 NYSERDA acknowledged limitations of the modeling approach and recognized several areas
42 where additional information could be collected to improve and refine erosion predictions for
43 future Phase 2 decision-making.

44



1
2 **Figure E-6 Observed (left) and “Best-fit” (right) Model Run Topography**

3 Image Credit: Figure F-8 (DOE, 2010)

4
5 **Potential Additional Data Collection Efforts**

6
7 DOE and NYSERDA commissioned an erosion working group to develop recommendations for
8 studies that could be conducted during Phase 1 to further reduce uncertainty associated with
9 the impact of erosion on site performance. The purpose of the additional studies would be to (i)
10 fill data gaps, (ii) produce converging lines of evidence, (iii) improve scientific defensibility, and
11 (iv) strengthen confidence in long-term erosion projections. DOE and NYSERDA are in the
12 process of evaluating the recommendations and will determine which Phase 1 studies will be
13 sponsored to provide additional support for erosion modeling predictions. A description of
14 recommended studies follows.

15
16 Phase 1 studies may include the following (EWG, 2012b):

17
18 1. Terrain Analysis

19
20 The purpose of terrain analysis would be to build on previous work cited in the FEIS to better
21 understand the post-glacial geomorphic history of the site and larger Buttermilk Creek
22 watershed. This would provide calibration information for the numerical model and constrain
23 important modeling parameters. For example, the geomorphic evolution of the Buttermilk Creek
24 watershed is likely more complicated than reflected in simplified calculations of stream
25 downcutting and valley rim widening rates based on limited age data. Stream downcutting may
26 be slowing over time due to a slowing of glacio-isostatic rebound since recession of the
27 Laurentide ice sheet. A better understanding of the geomorphic history of Buttermilk Creek may
28 enable better definition of critical parameter values used for erosion modeling. The terrain
29 analysis could include the following:

- 1
2
- Identification of elementary landforms or “land elements” using ArcMap (see Figure E-7a)
 - 3
 - 4 • Construction of geomorphic (land element) maps of WVDP, Buttermilk Creek, and potentially a companion basin site
 - 5
 - 6 • Performance of field reconnaissance to justify and verify potentials of mapped land elements
 - 7
 - 8 • Evaluation of available materials for age dating
 - 9 • Development of a conceptual framework for geomorphic history of Buttermilk Creek and its base level
 - 10

11 *2. Age Dating and Paleoclimate*

12
13 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:

- 21
- Excavation or examination of mapped “land elements” for age dating (Figure E-7b)
 - 23 • 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)
 - 25
 - 26 • Coring of tree rings to determine times of tree deformation from landslide movements and for locate climate proxy (drought)
 - 27
 - 28 • Dating of post-glacial erosional and depositional features
 - 29 • Evaluation of age data for possible correlation with Late Wisconsin glacial or postglacial climatic events
 - 30

31 *3. Recent Erosion and Depositional Processes*

32
33 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:

- 42
- Hillslope stability including characterization of rates and mechanisms of mass-wasting and landsliding
 - 44

- 1 • Rill and gully characterization including the mapping of locations and a determination of
- 2 the erodibility and erosivity of concentrated flow channels of critical concern, monitoring
- 3 of flow and sediment transport (if possible)
- 4 • Stream characterization including monitoring of flow and sediment transport (if possible),
- 5 assessment of knickpoint development and migration, and channel evolution (Figure
- 6 E-7d)
- 7 • Surface features including identification of erosional and depositional surface forms

8 4. Model Refinement, Validation and Improved Erosion Predictions

9
10 The purpose of the model refinement, validation and improved erosion prediction study would
11 be to (i) improve confidence in erosion modeling predictions through independent validation, (ii)
12 to reduce CHILD conceptual model and parameter uncertainty, and (iii) improve CHILD model
13 calibration. All of these activities would serve to increase confidence in the erosion modeling
14 predictions. Study 4 activities could include the following:

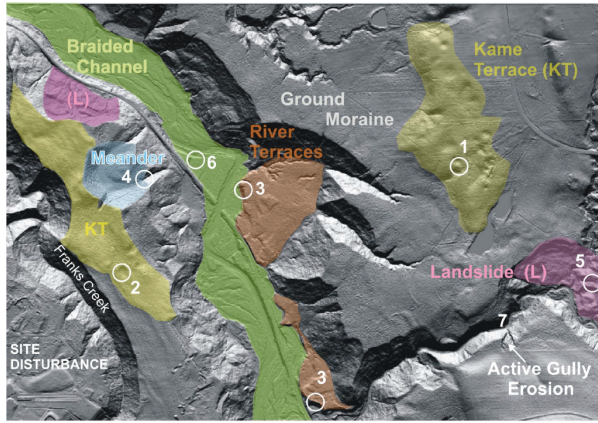
- 15
- 16 • Refine CHILD model parameters, structure, and calibration using data and information
- 17 collected in studies 1-3.
- 18 • Perform an independent validation test using calibrated model parameters to simulate a
- 19 second (companion) drainage basin that is comparable in dimensions to similar
- 20 landforms at WVDP.
- 21 • Project future erosion at the WVDP using refined and re-calibrated CHILD model;
- 22 perform sensitivity and uncertainty analysis, including evaluation of the sensitivity of the
- 23 results to climate.

24 How Does the West Valley Erosion Modeling Example Relate to 10 CFR Part 61 Guidance?

25
26 Although the West Valley erosion modeling example described above applies to a
27 decommissioning site and has not been fully executed by DOE and NYSERDA for NRC review,
28 the example illustrates many of the steps listed in Section 5.2.2 of this document, and
29 reproduced below for ease of reference, that may be taken to assess performance of a
30 10 CFR Part 61 facility¹.

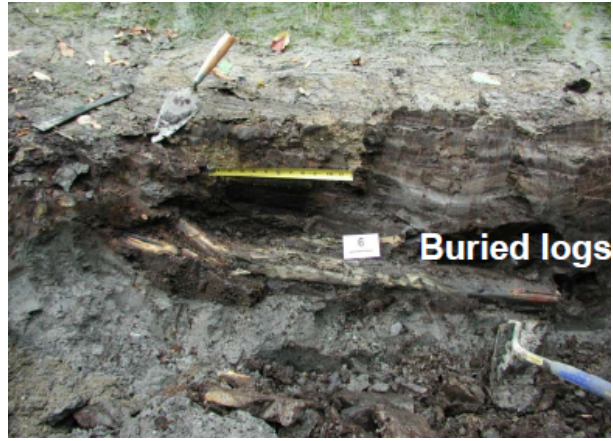
31
32

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.

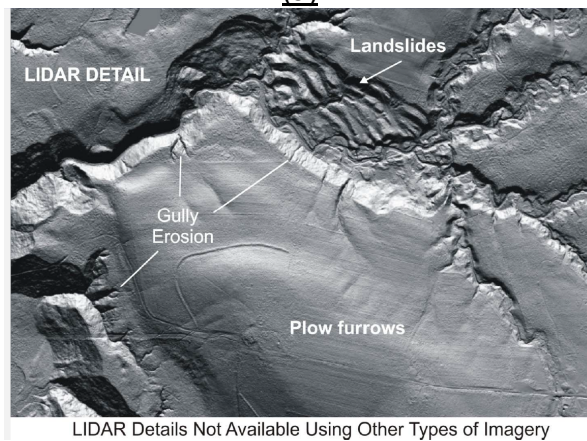


Example of Land Element Mapping (colors) with Dating/Prioritization Numbers

(a)



(b)



LIDAR Details Not Available Using Other Types of Imagery

(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:

- Define model objectives
- Develop or select the model
- Document and provide the basis for assumptions
- Parameterize the model
- Calibrate the model
- Verify the model
- Characterize uncertainty
- Provide model support
- Iterate, if necessary

1 Data collection and modeling of WVDP erosion has proceeded in an iterative fashion with
2 erosion analyses building on previous work and erosion modeling continuing to improve over
3 time as additional information is obtained. The code selection process began with the initial
4 evaluation of various shorter-term, smaller scale models that evaluated one or two key erosion
5 processes operable at the WNYNSC and WVDP but that were limited in their ability to simulate
6 multiple, coupled erosion processes over larger time and spatial scales. DOE also attempted
7 more sophisticated landscape evolution modeling using codes such as SIBERIA in earlier EIS
8 analyses. All of these modeling exercises led to the ultimate selection of the CHILD model that
9 is considered the state-of-the-art in landscape evolution modeling. Due to the complexity of the
10 site, landscape evolution modeling was considered necessary to provide technically defensible
11 erosion modeling predictions to facilitate consensus decision-making.

12
13 DOE used site-specific data or measurements, literature information from analog sites and
14 finally generic information sources, if more relevant data were not available to assign CHILD
15 modeling parameters. DOE used a calibration process to identify the most likely set of
16 parameter values to predict future erosion at the site. DOE also used site data and other
17 shorter-term modeling results to evaluate the reasonableness of CHILD modeling results. DOE
18 performed Monte Carlo analysis to evaluate the impact of parameter uncertainty on the results
19 of the analysis. DOE attempted to reduce uncertainty in the erosion predictions through
20 selection of “best-fit” parameter values in the calibration process that were able to produce
21 current day topography. DOE performed sensitivity analysis to evaluate “what-if” scenarios
22 such as a wetter climate or faster creep coefficients. DOE documented the results of its erosion
23 analyses in the FEIS including a discussion regarding potential model limitations. DOE
24 provided information on areas for potential improvement, including the collection and use of
25 additional data or additional analyses that might be conducted as code capabilities matured.
26 Phase 1 studies have been recommended by the WVDP erosion working group and will be
27 considered by DOE and NYSEDA to further reduce uncertainty and provide additional support
28 for erosion modeling predictions.

29
30 As indicated in Section 5.2.2.2, a model-based approach, similar to what was performed for
31 WVDP erosion modeling analyses, is typically used for longer-term analyses. A design-based
32 approach may also be justified for relatively shorter time periods. An example of a design-
33 based approach is provided in the next section. A hybrid approach may also be used for
34 assessments of site stability and could help provide multiple lines of evidence that the
35 performance objectives in 10 CFR Part 61, Subpart C will be met. For example, support may be
36 provided for the performance of a particular design for some period of time that mitigates the
37 risk of relatively short-lived waste. Over longer time periods, the performance of the design may
38 be less certain. Sensitivity analyses could be performed to evaluate the impact of various levels
39 of underperformance of the design over time to evaluate the acceptability of the design and the
40 ability of the site to meet performance objectives, lending confidence to the compliance and
41 performance period analyses. As illustrated in the next example, the model- and design-based
42 approaches share many common features (NRC, 2008).

43
44

Design-Based Approach: Moab UT Example:

FINAL
TECHNICAL EVALUATION REPORT

for the

PROPOSED REMEDIAL ACTION

of the

MOAB, UTAH
URANIUM MILL TAILINGS SITE

July 2008

Division of Waste Management
and Environmental Protection
Office of Federal and State Materials
and Environmental Management Programs
U.S. Nuclear Regulatory Commission

4.0 SURFACE WATER HYDROLOGY AND EROSION PROTECTION

4.1 Introduction

This section of the TER describes the staff's review of surface water hydrology and erosion protection issues related to long-term stability. In this section, the staff provides the technical bases for the acceptability of the licensee's erosion protection design. The RAP was reviewed against the EPA requirements presented in 40 CFR Part 192, Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings using Section 3.0 of the Final Standard Review Plan for the Review and Remedial Action of Inactive Mill Tailings Sites Under Title I of the Uranium Mill Tailings Radiation Control Act (NRC, 1993). Review areas that are covered include: estimates of flood magnitudes; water surface elevations and velocities; sizing of riprap to be used for erosion protection; long-term durability of the erosion protection; and testing and inspection procedures to be implemented during construction.

4.2 Hydrologic Description and Site Conceptual Design

To comply with 40 CFR 192, which requires stability of the tailings for 1000 years to the extent reasonably achievable and in any case for 200 years, DOE proposes to construct a disposal cell to protect the contaminated material from flooding and erosion. The design basis events for design of erosion protection include the Probable Maximum Precipitation (PMP) and the Probable Maximum Flood (PMF) events, both of which are considered to have very low probabilities of occurring during the 1000-year stabilization period.

As shown in Figure 6-3 of the Remedial Action Selection Report (RAS), the top surface of the cell will be configured to drain in various directions at a slope of about two percent, and the embankment side slopes will be constructed on a 1 vertical (V) on 5 horizontal (H) slope. To protect against erosion, the top and side slopes will be covered with layers of rock riprap. At the toes of the side slopes, rock riprap aprons will be constructed to provide protection against the potential migration of gullies toward the disposal cell. Several drainage channels will be constructed to convey flood flows off the disposal cell and away from the disposal area.

4.3 Flooding Determinations

The computation of peak flood discharges for various site design features was performed by DOE in several steps. These steps included: (1) selection of a design rainfall event; (2) determination of infiltration losses; (3) determination of times of concentration; (4) determination of appropriate rainfall distributions and intensities, corresponding to the computed times of concentration; and (5) calculation of flood discharge. Input parameters were derived from each of these steps and were then used to calculate the peak flood discharges to be used in the final determination of rock sizes for erosion protection.

4.3.1 Selection of Design Rainfall Event

One of the phenomena most likely to affect long-term stability is surface water erosion. To mitigate the potential effects of surface water erosion, the staff considers that it is very important to select an appropriately conservative rainfall event on which to base the flood protection designs. Further, the staff considers that the selection of a design flood event should not be based on the extrapolation of limited historical flood data, due to the unknown level of accuracy

associated with such an extrapolation. DOE utilized a PMP computed by deterministic methods (rather than statistical methods) and based on site-specific hydrometeorological characteristics. The PMP has been defined as the most severe reasonably possible rainfall event that could occur as a result of a combination of the most severe meteorological conditions occurring over a watershed. No recurrence interval is normally assigned to the PMP; however, the staff has concluded that the probability of such an event being equaled or exceeded during the 1000-year stability period is very low. Accordingly, the PMP is considered by the NRC staff to provide an acceptable design basis.

Prior to determining the runoff from the drainage basin, the flooding analysis requires the determination of PMP amounts for the specific site location. Techniques for determining the PMP have been developed for the United States by Federal agencies in the form of hydrometeorological reports for specific regions. These techniques are widely used and provide straightforward procedures with minimal variability. The staff, therefore, concludes that use of these reports to derive PMP estimates is acceptable.

PMP values were estimated by DOE using Hydrometeorological Report No. 49 (HMR-49). A 1-hour PMP of 8.2 inches was used by DOE as a basis for estimating PMFs for the small areas at the site such as the top and side slopes. These procedures for estimating PMP values were reviewed, and it was concluded that the PMP amounts are acceptable for the small drainage areas at the site.

4.3.2 Infiltration Losses

The determination of the peak runoff rate is also dependent on the amount of precipitation that infiltrates into the ground during its occurrence. If the ground is saturated from previous rains, very little of the rainfall will infiltrate and most of it will become surface runoff. The loss rate is highly variable, depending on the vegetation and soil characteristics of the watershed. Typically, all runoff models incorporate a variable runoff coefficient or variable runoff rates. Commonly-used models such as the U.S. Bureau of Reclamation (USBR) Rational Formula (USBR, 1977) incorporate a runoff coefficient (C); a C value of 1 represents 100% runoff and no infiltration. Other models such as the U.S. Army Corps of Engineers Flood Hydrograph Package HEC-1 (COE, 1988) separately compute infiltration losses within a certain period of time to arrive at a runoff amount during that time period.

In computing the peak flow rate for the small drainage areas at the site, DOE used the Rational Formula (USBR, 1977). In this formula, the runoff coefficient was assumed to be 1.0; that is, DOE assumed that no infiltration would occur. Based on its conservatism, the staff concludes that this is an acceptable assumption.

4.3.3 Times of Concentration

The time of concentration (t_c) is the amount of time required for runoff to reach the outlet of a drainage basin from the most remote point in that basin. The peak runoff for a given drainage basin is inversely proportional to the time of concentration. If the time of concentration is assumed to be smaller, the peak discharge will be larger. Times of concentration and/or lag times are typically computed using empirical relationships such as those developed by Federal agencies. Velocity-based approaches are also used when accurate estimates are needed.

Such approaches rely on estimates of actual flow velocities to determine the time of concentration of a drainage basin.

Times of concentration for the riprap design were estimated by DOE using an average of several methods, including the Kirpich Method (USBR, 1977). These methods are generally accepted in engineering practice and are considered by the staff to be appropriate for estimating times of concentration at this site. Based on a review of the calculations provided, the staff concludes that the t_c values used by DOE were acceptably derived.

4.3.4 Rainfall Distributions and Intensities

After the PMP is determined, it is necessary to determine the rainfall intensities corresponding to shorter rainfall durations and times of concentration. A typical PMP value is derived for periods of about one hour. If the time of concentration is less than one hour, it is necessary to extrapolate the data presented in the various hydrometeorological reports to shorter time periods.

To determine peak flood flows for the cell, DOE developed a rainfall depth-duration curve using guidelines in NUREG-1623 and calculated the rainfall intensities for the small drainage areas at the site to be about 28-54 inches per hour. Based on a review of this aspect of the flooding determination, the staff concludes that the computed peak rainfall intensities are acceptable.

4.3.5 Computation of PMF Discharges

To estimate PMF peak discharges for the top and side slopes, DOE used the Rational Method (Chow, 1959). This method is a simple procedure for estimating flood discharges that is recommended in NUREG-1623 (Johnson, 2002). In using the Rational Method, DOE assumed a runoff coefficient equal to 1.0 and a flow concentration factor of 3. For a maximum top slope length of about 1300 feet (with a slope of 0.02) and a side slope length of about 180 feet (with a slope of 0.2), DOE estimated the peak flow rates to be about 1.28 cubic feet per second per foot of width (cfs/ft) for the top slope and 1.33 cfs/ft for the side slope. PMF flow rates for the downstream aprons were estimated by DOE and are similar to the flow rates for the side slopes.

PMF flow rates for the channels were calculated by DOE and represent an accumulation of flows down the side slopes and offsite runoff. For the various channels and drainage structures, DOE used the SCS unit hydrograph method (USBR, 1987) to calculate peak PMF flows. Based on a review of the calculations, including the time of concentration, rainfall intensity, and runoff, the staff concludes that DOE's estimated flow rates are acceptable.

4.4 Erosion Protection

The ability of a riprap layer to resist the velocities and shear forces associated with surface flows over the layer is related to the size and weight of the stones which make up the layer. Typically, riprap layers consist of a mass of well-graded rocks which vary in size. Because of the variation in rock sizes, design criteria are generally expressed in terms of the median stone size, D_{50} , where the numerical subscript denotes the percentage of the graded material that contains stones of less weight. For example, a rock layer with a minimum D_{50} of 4 inches could contain rocks ranging in size from 0.75 inches to 6 inches; however, at least 50% of the weight of the layer will be provided by rocks that are 4 inches or larger. Depending on the rock source,

variations occur in the sizes of rock available for production and placement, and it is therefore necessary to ensure that these variations in rock sizes are not extreme. Design criteria for developing acceptable gradations are provided by various sources (e.g., Simons and Li, 1982), and examples of acceptable gradations may also be found in NUREG-1623.

4.4.1 Sizing of Erosion Protection

Riprap layers of various sizes and thicknesses are proposed for use at this site, and the design of each layer is dependent on its location and purpose. To reduce the number of gradations that need to be produced, DOE will place larger rock in some areas than is required. For ease of construction and to minimize the number of gradations, DOE has purposely over-designed several areas by providing larger rock than needed in many areas of the slopes and channels.

4.4.1.1 Top Slopes, Side Slopes, and Aprons

The portion of the top slope that drains to the south will be protected by a 6-inch thick layer of rock with a minimum D_{50} of about 1.8 inches. The area of the top slope draining to the north will be protected by a 6-inch layer of rock with a minimum D_{50} of 1.2 inches. Based on a review of the proposed gradation specifications, the minimum D_{50} that will be provided is about 2 inches, which is conservative.

For the north side slope of the cell, DOE proposes to use an 8-inch layer of rock with a minimum D_{50} of about 4 inches. The south side slope will be covered with a 12-inch layer of rock with a D_{50} of about 6 inches. The east and west side slopes will be protected by 6-inch layers of rock with a minimum D_{50} of 2 inches. Methods suggested in NUREG-1623 were used to determine the required rock sizes.

To protect the toe of the disposal cell and to dissipate the energy as the side slopes transition to natural ground, DOE will construct aprons along the toe of the side slopes. The area along the base of the south side slope will be protected by a rock toe/apron with a minimum D_{50} of 12 inches, while the toe of the north side slope will be protected by rock with a minimum D_{50} of 8 inches. The volume of rock was computed using a minimum depth of 3 times the D_{50} size and an apron width of 15 times the D_{50} size, or 10 feet, whichever is greater. The design criteria suggested in NUREG-1623 were used to determine rock sizes and rock volumes for the toe aprons.

Based on staff review of DOE's analyses and the acceptability of using design methods recommended by the NRC staff, the staff concludes that the proposed rock sizes for the top slopes, side slopes, and aprons are adequate.

4.4.1.2 Diversion Channels

DOE proposes to construct diversion channels at various locations in the area of the disposal cell. DOE developed peak PMF flows, rock sizes, and scour depths in accordance with methods recommended in NUREG-1623. Based on a check of the computations, the staff concludes that the peak flows, rock sizes, and scour depths are acceptable.

4.4.1.3 Channel Outlets

The diversion channels will extend several hundred feet past the edge of the disposal cell to prevent flows from directly impacting the cell side slopes. The channels will convey flows to the east and west sides of the cell and then will turn southward. At the end of the channels, the channels will be widened (termed flow “spreaders” by DOE). At the downstream end of the flow spreaders, additional rock will be provided to prevent gully headcutting into the spreaders. To reduce rock sizes to manageable levels, DOE intends to construct a pre-formed slope of 1V on 10H, and this slope will be extended to the expected scour depth. Staff review of the design of the riprap for the channel outlets indicates that the rock is large enough and extends to a sufficient depth to resist gully intrusion.

4.4.1.4 Sediment Considerations

The north side of the disposal cell would normally receive runoff directly from the area between Book Cliffs and the cell. This area will be protected by constructing a barrier using a very large quantity of excess excavated material (the “wedge”), which will act as a diversion berm to re-direct runoff away from the disposal cell. An access road between the cell and the wedge will be left in place. Runoff from the south side of the wedge will flow to the east and west in a ditch along the north side of the road, and runoff from the disposal cell will flow east and west along the south side of the road. See Figure 6-7 of the RAS.

The wedge will provide protection for the disposal cell by reducing the amount of runoff that is carried in the diversion channels to the north of the cell. Also, the wedge will reduce the amount of sediment entering the diversion channels. DOE performed sediment analyses to show that the wedge will accumulate sediment on its north side, but will be capable of re-directing flows away from the disposal cell.

DOE’s analyses indicate that sediment will be produced on the south slope of the wedge and that sediment from the wedge will fill and overtop the unlined channel north of the access road. This excess sediment will be deposited in the rock-lined channel south of the road. DOE provided analyses to show that the riprap sizes are large enough to resist the increased velocities associated with a reduction in channel capacity and an increase in discharges associated with overtopping of the unlined channel.

4.4.2 Riprap Gradations

Riprap gradations for each of the different rock sizes and layers were selected by DOE using basic gradation criteria. Based on review of the gradations provided, each layer thickness, gradation, and minimum rock size is acceptable.

4.4.3 Rock Durability

The previous sections of this TER examined the ability of the proposed erosion protection design to withstand flooding events reasonably expected to occur in a 1000- year period. In this section, rock durability is evaluated to determine if there is reasonable assurance that the rock itself is durable and will survive and remain effective for 1000 years. Rock durability is defined as the ability of the rock to withstand the forces of weathering. Therefore, rock durability is a key factor in evaluating the long-term stability of the rock cover. For rock to remain effective

to control erosion, the rock size selected should not be reduced by weathering processes. Therefore, if the rock size used for the cover does not diminish over the 1000-year compliance period, its ability to control future erosion will be sustained. However, uncertainties exist with estimating future rock durability for 1000 years. As a result, NRC guidance identifies three evaluations of rock durability to provide multiple and complimentary lines of evidence and greater confidence in the sustained durability of the rock source selected. These evaluations are: 1) rock durability testing and scoring; 2) absence of adverse minerals and heterogeneities; and 3) evidence of resistance to weathering. Information for each of these evaluations was provided by DOE and the staff's review is described below.

4.4.3.1 Selection and Description of Rock Type and Source

Description of the rock types and deposit that is proposed for the rock source is important to understanding the variability of the deposit or formation containing the proposed rock source (e.g. percentage of each rock type), and the variability within the proposed rock source (e.g. different fabrics that could affect rock durability and resistance to weathering). Understanding the variability of the deposit/formation and each rock type are important to obtaining representative samples for durability tests and developing rock production procedures that may be needed to mitigate adverse rock types in the deposit/formation.

DOE has selected a basalt as a rock source from a site approximately four miles east of Fremont Junction, Utah, which is approximately 95 miles west of the Crescent Junction site. NRC approved DOE's use of this rock source in 1988 for its use in the erosion cover for the Green River UMTRA disposal cell in Green River, Utah. The Fremont Junction site consists of 400 acres of property owned by the State of Utah School of Institutional Trust Lands Administration that has been permitted for the purpose of mining ordinary sand and gravel. The basalt-bearing deposit at the Fremont Junction site is a Quaternary pediment-mantling alluvial deposit of Quaternary age.

DOE's selection of the Fremont Junction basalt is based on the combined results of the 1988 evaluations of the basalt for the Green River disposal cell and the recent studies in 2007 and 2008 for the Crescent Junction site. The 1988 evaluations consisted of field observations at two test pits, durability tests, petrographic analyses, and x-ray diffraction analyses. The 2007 and 2008 evaluations include field observations at eight test pits, durability tests, observations of the basalt on the Green River disposal cell, and natural analogue studies that provide evidence of long-term resistance to weathering. The basalt used at Green River was excavated from the same alluvial deposit about one mile northeast of the areas that would be excavated for the Crescent Junction site. Therefore, the 1988 petrographic analyses and x-ray diffraction analyses were used and not repeated in 2008.

The Fremont Junction deposit includes an overburden layer at the surface that is approximately eight feet thick that consists of clayey sand and clayey silt with a small percent of basalt clasts with caliche crusts, a reddish relic soil layer, and in places a white calcified zone. Beneath the overburden layer is the alluvial deposit that is at least 20 feet thick and consists of 15-45 % subrounded cobbles and boulders of basalt and other rock types such as tan sandstone, limestone, chert, and quartzite. Matrix material supports the cobbles and boulders and consists of sand and gravel up to three inches. DOE's rock production procedures discussed in Section 4.4.4, include screening to separate the matrix material from the cobbles and boulders of basalt and non-basalt that would then be crushed to the sizes specified for use as cover material.

Based on the estimates of rock types and alluvial deposit thickness, DOE estimates that the volume of useable rock should be at least twice the volume required by the design of the erosion cover.

DOE estimates that the cobble and boulder portion of the alluvial deposit includes about 95% dark gray basalt and 2-3% red basalt. These two types of basalt were likely derived from two different sources that are 15 to 20 miles southwest and south-southwest of the site. The remaining non-basalt lithologies in the alluvial deposit make up about 2-3%. The tan sandstone and limestone cobbles and boulders are soft and nondurable, whereas the chert and quartzite cobbles appeared to be at least as hard and durable as the basalt. The estimates of the non-basalt lithologies and their respective rock durability scores are important to conclusions about how much of this material is acceptable and unacceptable for use. The rock production procedures in Section 4.4.4 discuss how the unacceptable material, such as the tan sandstone, would be removed from the deposit either by crushing, which would reduce its percentage further, or removal of the boulders before crushing.

4.4.3.2 Rock Durability Testing and Scoring

Rock durability testing and scoring following the procedures in NRC's guidance in NUREG-1623 is one of the evaluations DOE used for determining the acceptability of the Fremont Junction rock source for its Crescent Junction erosion protection cover. This evaluation procedure provides a consistent and quantitative way to evaluate rock sources at NRC regulated sites using ASTM tests for parameters that are good indicators of rock durability (i.e., specific gravity, absorption, sodium sulfate soundness, and L/A abrasion).

DOE provided durability test data of samples from the Fremont Junction area collected in 1988 and 1989 for the Green River disposal cell and in 2007 and 2008 for the Crescent Junction site. Tests were conducted on samples from the gray and red basalts. Results from specific gravity, absorption, sodium sulfate soundness, and L/A abrasion tests were provided and then used to develop rock scores following NRC's guidance in NUREG-1623.

The scores of the 1988 samples for the Green River disposal cell ranged from 66.7% to 79.4%. The sample that scored 66.7% was described in the 1988 report as severely weathered. However, DOE's 2008 evaluation concludes that these samples were likely the vesicular red basalt. DOE's 1988-1989 quality control testing and scoring of four samples collected during the placement of the basalt cover at the Green River disposal cell resulted in additional and higher scores for the Fremont Junction basalt. Scores for the Type A rip rap ranged from 78 to 90% with an average of 85%. Scores for the Type B rip rap ranges from 80 to 90 % with an average of 83%.

DOE's scores from the 2007 and 2008 samples provided additional results. The gray basalt, which makes up approximately 95% of the alluvial deposit, had scores of 82.9 and 83.3. These scores exceed the 80% score that indicates a high quality rock that can be used for most applications according to NRC's guidance. The red basalt that makes up approximately 2-3% of the basalt had a score of 63.7 which is similar to the 1988 initial score. Although the 63.7% score is lower than the gray basalt, it is in the range for rock that would be acceptable for use in non critical areas. DOE noted that the sample of the red basalt was softer than the gray basalt; possibly because it was vesicular. During the June 25, 2008 site visit, field observations of

cobbles and boulders of dense non-vesicular red basalt appeared to both DOE and NRC staff to be more competent than the vesicular red basalt that had a low score.

4.4.3.3 Absence of Adverse Minerals and Heterogeneities

DOE used information from field observations and the 1988 petrographic and x-ray diffraction analyses to identify if adverse heterogeneities or adverse minerals were present that could be vulnerable to weathering. Field observations were used to identify large scale adverse heterogeneities such as the undesirable overburden layer and fine grained matrix sediments supporting the cobbles and boulders in the overall deposit. As discussed in Section 4.4.1, DOE proposes to remove the overburden layer before excavation of the basalt alluvial deposit. DOE also proposes to screen out the finer matrix material from the basalt cobbles and boulders.

The petrographic and x-ray diffraction analyses were used to identify if adverse minerals that could be susceptible to weathering, such as olivine and clay, are present and if so in what amounts. DOE's 1988 petrographic analyses concluded that the samples lacked significant amounts of adverse minerals such as calcite, clays, olivine, and feldspaths. X-ray diffraction analyses determined that the basalt samples contained only 1% olivine.

The field observations and petrographic analyses also identified the non-basalt lithologies in the deposit and those lithologies that might be unacceptable and excluded by rock processing procedures. The non-basalt lithologies making up about 2-3% of the cobbles and boulders, consist of tan sandstone, limestone, chert, and quartzite. The sandstone appeared to be friable in field observations. The petrographic analysis of the sandstone indicated surface weathering is moderate and consists of pitting due to leaching of carbonate grains that penetrated one quarter of an inch. The 6% calcite occurred as recrystallized limestone grains and the 5% clay occurred as rock fragments. Although this undesirable sandstone makes up a very small part of the cobbles and boulders, as discussed in Section 4.4.1, DOE proposes to minimize this lithology by crushing and screening as well as removal of large boulders, if necessary.

4.4.3.4 Evidence of Resistance to Weathering

Evidence of resistance to weathering can be both direct and indirect. DOE's 2007 and 2008 field observations of the eight test pits did not show evidence of significant weathering of the basalt such as weathering rinds. To confirm these observations and to resolve the 1988 report of an upper weathered zone and weathering rinds on the red basalt, DOE also observed the crushed basalt used on the cover of the Green River disposal cell and the subrounded basalt boulders in the Green River channel. This basalt from the same deposit at Fremont Junction provided a large "exposure" of the basalt that was clean and free of the fine material and dust that limited observations in the test pits at Fremont Junction. DOE did not observe any weathering rinds on either the dark gray or red basalt. DOE concluded that the descriptions of weathering rinds from the 1988 investigation possibly were interpreted to be the thick caliche crusts on some basalt clasts. Thus, more recent DOE investigations, as well as NRC observations during a site visit, confirm the absence of weathering zones or weathering rinds on the Fremont Junction basalt.

The only evidence of basalt weathering was the leaching of olivine crystals by chemical weathering on the surface of a sample observed in the 1988 petrographic analyses. This analysis also noted that the olivine crystals observed in the interior of the sample had not been

weathered. As mention above, the x-ray diffraction analysis indicated that olivine only made up 1% of the sample analyzed.

Because of the absence of quantitative weathering rate studies for basalt as well as other rock types, NRC's guidance in NUREG-1757 notes that indirect evidence of resistance to weathering can add confidence in the durability and slow weathering of rock types selected for long-term erosion protection. DOE identified the following geologic analogues to show that the Fremont Junction basalt has remained resistant to weathering for thousands of years and well beyond the 1000-year regulatory period required.

- Basalt boulders may have resisted weathering for 500,000 years based on the estimated age of the alluvial deposit, using a published steam downcutting rate for this part of the Colorado Plateau.
- Basalt boulders have resisted weathering for possibly 8,000 to 10,000 years based on the estimated age of wind-fluted surfaces on exposed basalt boulders caused by wind driven sand.
- Rock varnish on exposed basalt boulders may have been formed several thousand years ago.
- Lichen cover on exposed basalt boulders may have been in place for hundreds of years.
- Basalt boulders buried at depths of three to six feet in the overburden commonly have white calcium carbonate crusts, which can take tens of thousands of years to form, indicating these boulders have been in place for many thousands of years without noticeable weathering effects.

4.4.3.5 Conclusions

Based on the review of DOE's evaluations, the staff concludes that: 1) durability test results and scores demonstrate acceptable physical properties of the Fremont Junction basalt; 2) adverse minerals such as olivine and clay are present in very small amounts (1%) and adverse heterogeneities, such as friable sandstone and matrix sand and gravel, can be identified and avoided when rock is excavated or screened and crushed in processing; 3) there is direct evidence from the Fremont Junction deposit and Green River disposal cell cover of the absence of weathering such as weathering rinds; and 4) indirect evidence from natural basalt analogues add confidence that basalt weathering rates are slow and the basalt has resisted weathering for thousands of years at the Fremont Junction area. Based on these evaluations, the staff concludes that the Fremont Junction basalt is durable and should resist weathering and associated size reduction for at least the 1000 year compliance period. Therefore, the staff considers that the Fremont Junction basalt is acceptable for use in the erosion controls at the Crescent Junction site. This conclusion is consistent with NRC's previous approval of the basalt for use at the Green River disposal cell.

4.4.4 Testing and Inspection of Erosion Protection

DOE provided information regarding testing, inspection, and quality control procedures to be used for the erosion protection materials.

4.4.4.1 Rock Selection During Production

As discussed above, DOE has selected the Fremont Junction basalt as its rock source. Based on information provided by DOE in Sections 6.6 and 6.7 of the RAP and as discussed above in Section 4.4.3.1, it appears that the rock in the proposed quarry could be somewhat variable, depending on the location where rock will be produced within the quarry. DOE provided information to document the quality assurance and quality control (QA/QC) procedures that will be implemented during rock production to address this variability and to assure that rock of acceptable quality will consistently be produced.

The overall goal of the rock selection procedure is to minimize the potential that unsuitable rock is produced. To accomplish this, DOE intends to strip overburden from the alluvial deposits and to stockpile this material in a manner where it is separated from the basalt cobbles and boulders. Rock materials will be excavated, crushed, and screened into stockpiles of various sizes. The rock will then be crushed and further screened, as necessary, to produce the required rock sizes. These primary and secondary sorting processes should assure that rock will be relatively homogeneous and that visible portions of the stockpiles will be representative of the entire stockpile. Crushing and screening will also remove significant amounts of weak, friable materials (i.e., tan sandstone and limestone), resulting in a product that contains only limited amounts of poor-quality materials. In the unlikely event that a stockpile contains significant unacceptable rock, the lower quality material (i.e., tan friable sandstone and limestone) would be extracted to assure that no more than 10% by volume is present in the final product.

On June 26, 2008, the staff directly observed the Fremont Junction site. Based on observations during that site visit and information provided by DOE in Sections 6.6 and 6.7 of the RAP, the staff concludes that the proposed program for rock production is acceptable.

4.4.4.2 Durability Testing

DOE proposes that rock durability testing will be performed a minimum of four times and/or at a frequency of one test for every 10,000 cubic yards of material produced. This testing frequency is recommended in NUREG-1623 and is equivalent to others approved by the staff and have been implemented at other reclaimed sites during construction.

DOE's proposed rock durability testing program will include the following tests, shown with their American Society of Testing and Materials (ASTM) designation:

1. Bulk Specific Gravity - ASTM C 127
2. Absorption - ASTM C 127
3. Sodium Sulfate Soundness - ASTM C 88
4. L.A. Abrasion at 100 cycles - ASTM C 131 or ASTM C 535
5. Schmidt Rebound Hardness - ISRM Method

Based on a review of the proposed procedures, the staff concludes that an acceptable durability testing program has been provided to ensure that rock of acceptable quality will be provided. The testing program was developed using suggested staff guidance in NUREG-1623 and is equivalent to several which were approved by the staff and have been implemented at other reclaimed sites during construction.

4.4.4.3 Gradation Testing

DOE proposes that rock gradation testing for each gradation will be performed a minimum of four times and/or at a frequency of one test for every 10,000 cubic yards of material placed. This testing frequency is recommended in NUREG-1623 and is equivalent to others approved by the staff and have been implemented at other reclaimed sites during construction.

4.4.4.4 Riprap Placement

DOE indicates that riprap will be placed using a computerized placement method where the equipment is calibrated to assure that proper thicknesses of rock are placed. In addition, DOE provided specifications for placement of the rock that will confirm that the riprap layers will be placed to the depths and grades shown on the drawings and that riprap will be placed in a manner to ensure that areas of segregation do not exist. Based on a review of the information provided by DOE, the staff concludes that the proposed procedures are sufficient to ensure acceptable placement of the riprap.

4.5 Conclusions

Based on review of the information submitted by DOE and on independent calculations, the NRC staff concludes that sufficient information has been provided to justify that the erosion protection design is adequate to provide reasonable assurance of protection for 1000 years, as required by 40 CFR 192.



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4 **Figure E-8 Example of an Erosion Protection Cover for Uranium Mill Tailings**

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NRC FORM 335 (12-2010) NRCMD 3.7	U.S. NUCLEAR REGULATORY COMMISSION 1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG-2175				
BIBLIOGRAPHIC DATA SHEET (See instructions on the reverse)					
	2. TITLE AND SUBTITLE Title: Guidance for Conducting Technical Analyses for 10 CFR Part 61 Subtitle: Draft Report for Public Comment	3. DATE REPORT PUBLISHED <table border="1"> <tr> <td>MONTH</td> <td>YEAR</td> </tr> <tr> <td>March</td> <td>2015</td> </tr> </table> 4. FIN OR GRANT NUMBER	MONTH	YEAR	March
MONTH	YEAR				
March	2015				
5. AUTHOR(S) D. Esh, C. Grossman, H. Arlt, C. Barr, P. Yadav	6. TYPE OF REPORT Technical				
8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.) Division of of Decommissioning, Uranium Recovery, and Waste Programs Office of Nuclear Material Safety and Safeguards U.S. Nuclear Regulatory Commission Washington, DC 20555-0001	7. PERIOD COVERED (Inclusive Dates)				
9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.) Same as above					
10. SUPPLEMENTARY NOTES					
11. ABSTRACT (200 words or less) This document provides guidance on conducting technical analyses (i.e., performance assessment, inadvertent intruder assessment, assessment of the stability of a low-level waste disposal site, defense-in-depth analyses, protective assurance period analyses, and performance period analyses) to demonstrate compliance with the performance objectives in Title 10 of the Code of Federal Regulations (10 CFR) Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste." This document provides implementing guidance for amendments to 10 CFR Part 61 that are detailed in the proposed rule, "Low-Level Radioactive Waste Disposal," published in the Federal Register in 2015. The guidance in this document is intended to supplement existing low-level radioactive waste guidance on issues pertinent to conducting technical analyses to demonstrate compliance with the performance objectives. This document provides detailed guidance in new areas that are less covered in existing guidance, such as the inadvertent intruder analysis, defense-in depth analyses, and analyses for the three phases of the analysis timeframe (compliance period, protective assurance period, and performance period). This guidance discusses the use of a graded level of effort needed to risk-inform the analyses for the compliance period (1,000 years), the protective assurance period (from 1,000 years to 10,000 years after disposal site closure), and also covers the performance period analyses that should be performed for analysis of long lived waste beyond 10,000 years. This guidance should facilitate licensees' implementation of the proposed amendments as well as assist regulatory authorities in reviewing the technical analyses. This guidance applies to all waste streams disposed of at a 10 CFR Part 61 low-level waste disposal facility, including large quantities of depleted uranium and blended waste.					
12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.) performance assessment, dose assessment, low-level waste disposal, 10 CFR Part 61 compliance, 10 CFR Part 61 performance objectives, time of compliance, period of performance, scenario development, uncertainty analysis, intruder assessment, inadvertent intruder, waste acceptance, site stability analyses, performance period analyses, long-lived waste, depleted uranium, site-specific analyses, technical analyses, concentration averaging, blending, protective assurance period	13. AVAILABILITY STATEMENT unlimited				
	14 SECURITY CLASSIFICATION (This Page) unclassified				
	(This Report) unclassified				
	15. NUMBER OF PAGES				
16. PRICE					



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Guidance for Conducting Technical Analyses for 10 CFR Part 61

March 2015