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2.2 SCENARIO ANALYSIS AND EVENT PROBABILITY

Scenario Analysis and Event Probability describes the identification, classification, screening, and construction of scenario classes from the features, events, and processes (FEPs) considered at the Yucca Mountain Site. This section also addresses those FEPs necessary to describe the future evolution of the repository system. Scenario analysis is a systematic enumeration of FEPs that can reasonably occur in the repository system and is a starting point for the performance assessment. Scenario analysis facilitates the identification of possible ways in which the geologic repository environment can evolve, so a representation of the system can be implemented in the performance assessments. The information presented in this section describes the limits on performance assessments required by proposed 10 CFR 63.342.

The information presented below summarizes the content of Section 2.2, the corresponding regulatory requirements, and the applicable acceptance criteria from NUREG-1804.

SAR Section	Information Category	Proposed 10 CFR Part 63 Reference	NUREG-1804 Reference
2.2	Scenario Analysis and Event Probability	63.21(c)(1)[a] 63.21(c)(9)[a] 63.102(j)[a] 63.102(k)[a] 63.114(a)(1) 63.114(a)(2) 63.114(a)(4) 63.114(a)(5) 63.114(a)(6) 63.114(a)(7) 63.114(b) 63.322[a] 63.342	Section 2.2.1.2.1.3: Acceptance Criterion 1 Acceptance Criterion 2 Acceptance Criterion 3 Acceptance Criterion 4 Section 2.2.1.2.2.3: Acceptance Criterion 1 Acceptance Criterion 2 Acceptance Criterion 3 Acceptance Criterion 4 Acceptance Criterion 5 Section 2.2.1.3.1.3: Acceptance Criterion 1(6) Section 2.2.1.3.2.3: Acceptance Criterion 1(6) Section 2.2.1.3.3.3: Acceptance Criterion 1(11) Acceptance Criterion 2(5) Acceptance Criterion 3(5) Section 2.2.1.3.4.3: Acceptance Criterion 1(7) Acceptance Criterion 3(6) Acceptance Criterion 3(7) Section 2.2.1.3.7.3: Acceptance Criterion 3(3) Section 2.2.1.3.9.3: Acceptance Criterion 3(3)
2.2.1	Analysis of FEPs and Scenario Classes	See details in sections below	See details in sections below
2.2.1.1	Identification and Classification of FEPs	63.102(j)[a]	Section 2.2.1.2.1.3: Acceptance Criterion 1

SAR Section	Information Category	Proposed 10 CFR Part 63 Reference	NUREG-1804 Reference
2.2.1.2	Screening of FEPs	63.21(c)(9)[a] 63.114(a)(4) 63.114(a)(5) 63.114(a)(6) 63.342	Section 2.2.1.2.1.3: Acceptance Criterion 2[b] Section 2.2.1.3.3.3: Acceptance Criterion 2(5) Section 2.2.1.3.4.3: Acceptance Criterion 3(7)
2.2.1.3	Event Class and Scenario Class Formation	63.102(j)[a] 63.114(b)	Section 2.2.1.2.1.3: Acceptance Criterion 3
2.2.1.4	Screening of Scenario Classes and Event Classes	63.21(c)(9)[a] 63.102(j)[a] 63.342	Section 2.2.1.2.1.3: Acceptance Criterion 4 Section 2.2.1.3.1.3: Acceptance Criterion 1(6) Section 2.2.1.3.2.3: Acceptance Criterion 1(6) Section 2.2.1.3.3.3: Acceptance Criterion 1(11) Acceptance Criterion 3(5) Section 2.2.1.3.4.3: Acceptance Criterion 1(7) Acceptance Criterion 3(6) Section 2.2.1.3.7.3: Acceptance Criterion 3(3) Section 2.2.1.3.9.3: Acceptance Criterion 3(3)
2.2.2	Identification of Events with Probabilities Greater Than 1 Chance in 10,000 of Occurring over 10,000 Years	See details in sections below	See details in sections below
2.2.2.1	Seismic Activity	63.21(c)(1)[a] 63.21(c)(9)[a] 63.102(j)[a] 63.114(a)(1) 63.114(a)(2) 63.114(a)(4) 63.114(a)(7) 63.114(b) 63.342	See details in sections below
2.2.2.1.1	Probability of a Seismic Event	63.21(c)(1)[a] 63.21(c)(9)[a] 63.102(j)[a] 63.114(a)(4) 63.342	Section 2.2.1.2.2.3: Acceptance Criterion 1 Acceptance Criterion 2 Acceptance Criterion 4
2.2.2.1.2	Technical Bases of Probability Estimates	63.21(c)(1)[a] 63.114(a)(1)	Section 2.2.1.2.2.3: Acceptance Criterion 2
2.2.2.1.3	Adequacy of Probability Model Support	63.114(a)(7)	Section 2.2.1.2.2.3: Acceptance Criterion 3
2.2.2.1.4	Probability Model Parameters	63.21(c)(1)[a] 63.114(a)(1)	Section 2.2.1.2.2.3: Acceptance Criterion 4

SAR Section	Information Category	Proposed 10 CFR Part 63 Reference	NUREG-1804 Reference
2.2.2.1.5	Uncertainty in Event Probability	63.114(a)(2)	Section 2.2.1.2.2.3: Acceptance Criterion 5
2.2.2.2	Igneous Activity	63.21(c)(1)[a] 63.21(c)(9)[a] 63.102(j)[a] 63.114(a)(1) 63.114(a)(2) 63.114(a)(4) 63.114(a)(7) 63.114(b) 63.342	See details in sections below
2.2.2.2.1	Probability of an Igneous Event Intersecting the Repository	63.21(c)(1)[a] 63.21(c)(9)[a] 63.102(j)[a] 63.114(a)(4) 63.342	Section 2.2.1.2.2.3: Acceptance Criterion 1 Acceptance Criterion 4
2.2.2.2.2	Technical Bases of Probability Estimates	63.21(c)(1)[a] 63.114(a)(1)	Section 2.2.1.2.2.3: Acceptance Criterion 2
2.2.2.2.3	Probability Model Support	63.114(a)(7)	Section 2.2.1.2.2.3: Acceptance Criterion 3
2.2.2.2.4	Probability Model Parameters	63.21(c)(1)[a] 63.114(a)(1)	Section 2.2.1.2.2.3: Acceptance Criterion 4
2.2.2.2.5	Uncertainty in Event Probability	63.114(a)(2)	Section 2.2.1.2.2.3: Acceptance Criterion 5
2.2.2.3	Early Waste Package and Drip Shield Failures	63.21(c)(9)[a] 63.102(j)[a] 63.114(a)(4) 63.114(b) 63.342	Section 2.2.1.2.2.3: Acceptance Criterion 1(1) Acceptance Criterion 4
2.2.2.4	Human Intrusion	63.102(k)[a] 63.322[a]	Section 2.2.1.2.2.3: Acceptance Criterion 1(1)

NOTE: [a]Not changed by the proposed rule.
[b]Exclusion justifications are found in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008a).

Conducting a total system performance assessment (TSPA) for the repository requires a large amount of information and a variety of mathematical models. However, at a conceptual level, the implementation of a TSPA requires answers to four basic questions:

- What events and processes can take place at the facility under consideration?
- How likely are these events and processes to take place?
- What are the consequences of individual occurrences of these events and processes?
- How reliable are the answers to the first three questions?

Answers to these questions begin with identifying and screening FEPs that may have relevance to the TSPA. In particular, the FEP identification and screening process gathers, assesses, and selects the information that ultimately leads to the formal computational structure and associated calculations that quantitatively address the topics of the last three questions: probabilities, consequences, and uncertainty assessments (SNL 2008b, Appendix J).

The first and second questions include the occurrence and likelihood of events that take place in the future. These questions are the focus of Section 2.2. Such occurrences are assumed to have a random character because, although it is possible to estimate the likelihood of their taking place over various intervals of time, it is not possible to determine whether or not they will actually occur or the exact time of occurrence. Such uncertainty as a result of randomness is referred to as aleatory uncertainty. Examples of aleatory uncertainty include the occurrence of seismic events, igneous events, and particular spatial patterns of corrosion (SNL 2008b, Appendix J).

The third question relates to determining the consequences of events or processes that could occur in the repository system by modeling the physical behavior of the system. Such models predict consequences for a specified sequence of events. Coupled system models, which are constructed by combining many individual models, are common in performance assessment for radioactive waste disposal. The performance assessment includes the development, parameterization, and numerical evaluation of models used to predict the consequences associated with particular occurrences (e.g., seismic events) (SNL 2008b, Appendix J).

The fourth question relates to a second type of uncertainty related to the model abstractions and parameters used in the TSPA model. Such uncertainty is often referred to as epistemic uncertainty. Epistemic uncertainty arises with respect to parameters or models because data are limited or because there are alternative interpretations of available data. The third and fourth questions are the focus of Sections 2.3 and 2.4.

The U.S. Department of Energy (DOE) uses a TSPA to demonstrate compliance with the postclosure individual protection standards of proposed 10 CFR 63.311 and proposed 10 CFR 63.321 and the groundwater protection standards of 10 CFR 63.331.

The NRC defines a performance assessment at 10 CFR 63.2 as modified in proposed 10 CFR 63.2 as an analysis that:

1. Identifies the features, events, processes (except human intrusion), and sequences of events and processes (except human intrusion) that might affect the Yucca Mountain disposal system and their probabilities of occurring

2. Examines the effects of those features, events, processes, and sequences of events and processes upon the performance of the Yucca Mountain disposal system

3. Estimates the dose incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases caused by all significant features, events, processes, and

> sequences of events and processes, weighted by their probability of occurrence (70 FR 53313, p. 53318).

Section 2.2.1 describes FEP identification and screening to address the first element of the first performance assessment requirement. Section 2.2.2 describes event probability to address the second element of the first performance assessment requirement. Section 2.3 describes the models, parameters, and data used to address the second performance assessment requirement. The third requirement of performance assessment is addressed in Section 2.4.2.

2.2.1 Analysis of FEPs and Scenario Classes

[NUREG-1804, Section 2.2.1.2.1.3: AC 1, AC 2, AC 3, AC 4]

Scenario analysis for the purposes of postclosure performance assessment, consists of the following five steps (SNL 2008c, Section 1):

1. Identify and classify FEPs potentially relevant to the long-term postclosure performance of the disposal system.

2. Evaluate the FEPs to identify those FEPs that should be included in or excluded from the performance assessments that are conducted to demonstrate compliance with proposed 10 CFR 63.311(a)(1), proposed 10 CFR 63.321(b)(1), and 10 CFR 63.331. This is referred to as screening the FEP.

3. Form appropriate event classes and scenario classes from the FEPs for the purpose of further screening or analyses. Events are used to form event classes and scenario classes.

4. Screen the scenario classes and event classes, using the same screening criteria applied to individual FEPs, to identify any scenario classes that can be excluded from each of the performance assessments conducted to demonstrate compliance with proposed 10 CFR 63.311(a)(1), proposed 10 CFR 63.321(b)(1), and 10 CFR 63.331.

5. Specify the implementation of the scenario classes in the computational modeling for the TSPA, and document the treatment of FEPs that were included.

The first four steps in the approach described above are based on the organization of the acceptance criteria presented in NUREG-1804, Section 2.2.1.2.1.3, and are discussed in more detail in Sections 2.2.1.1 to 2.2.1.4. The fifth step described above, while not specifically included in Section 2.2.1.2.1 of NUREG-1804, is introduced in Section 2.2.1.3, discussed in Section 2.3, and synthesized in Section 2.4.1.

The following definitions are used to support the FEP analysis process:

- **Features**—Features are physical, chemical, or thermal characteristics of the site or repository system. For the purposes of identification, classification, and screening of FEPs, a feature is defined as an object, structure, or condition that has a potential to affect disposal system performance (NUREG-1804, Glossary). The waste package is an example of a feature.

- **Events**—Events are occurrences that have a specific starting time and, usually, a duration shorter than the time being simulated in a model. For the purposes of identification, classification, and screening of FEPs, an event is defined as a natural or human-caused phenomenon that has a potential to affect disposal system performance and that occurs during an interval that is short compared with the period of performance (NUREG-1804, Glossary). An example of an event is igneous intrusion into the repository.

- **Processes**—Processes are phenomena and activities that have gradual, continuous interactions with the system being modeled. For the purposes of identification, classification, and screening of FEPs, a process is defined as a natural or human-caused phenomenon that has a potential to affect disposal system performance and that operates during all or a significant part of the period of performance (NUREG-1804, Glossary). General corrosion of the waste package is an example of a process.

The subsequent sections summarize the process for identification and classification of FEPs potentially relevant to the postclosure performance of the disposal system (Section 2.2.1.1), the screening process to determine the FEPs that can be excluded from the performance assessments and those that are included in the performance assessment compliance analyses (Section 2.2.1.2), the formation of scenario classes resulting from the included FEPs (Section 2.2.1.3), and the scenario classes that are excluded from the TSPA (Section 2.2.1.4).

2.2.1.1 Identification and Classification of FEPs
[NUREG-1804, Section 2.2.1.2.1.3: AC 1]

In Step 1 of the FEP analysis and scenario development process, FEPs potentially relevant to postclosure performance are identified and classified. The primary objectives of FEP identification and classification are to develop a comprehensive set of FEPs for analysis and to provide a framework for developing and organizing scenario classes.

The identification and classification of a comprehensive list of FEPs potentially relevant to postclosure performance for Yucca Mountain was an iterative process based on site-specific information, design, and regulations. The early history of FEP identification and classification is summarized in *An International Database of Features, Events, and Processes* (NEA 1999, pp. 16 to 17) and includes international reviews (IAEA 1983) and reviews by the U.S. Nuclear Regulatory Commission (NRC) (Cranwell et al. 1990).

The formal FEP analysis process was initiated to support the site recommendation and continued through preparation of the license application. The iterative FEP analysis process is based, in part, on some general considerations for FEP identification and classification that are derived from other radioactive waste disposal programs. In particular, confidence in the comprehensiveness of a FEP list (e.g., confidence that the identification of a list of FEPs is adequate) can be gained through a combination of formal and systematic reviews, audits, and comparisons with other FEP lists and through the application of more than one classification scheme (SNL 2008c, Section 6.1).

2.2.1.1.1 FEP Identification

FEP identification methods (NEA 1999, pp. 26 to 27) include (1) development from an existing detailed FEP list, (2) brainstorming (e.g., freely-structured identification by groups of relevant experts), (3) top-level-down elicitation from a classification scheme, and (4) hybrid procedures combining the other three methods.

Prior to the TSPA for site recommendation, there was no formal FEP list for Yucca Mountain, but informal FEP identification activities were performed starting as early as 1988 (Freeze et al. 2001, Section 2.2). FEP identification for site recommendation applied fully or in part all four of the common FEP identification methods, as summarized below:

- **Method 1: Existing List**—Used Version 1.0 of the Nuclear Energy Agency International FEP Database (Safety Assessment Management 1997) as a basis for the initial FEP list, augmented by site-specific information (Freeze et al. 2001, Section 2.1).

- **Method 2: Brainstorming**—Used to develop some of the initial project-specific FEPs in project documents and to identify FEPs by subject matter experts during technical workshops and reviews (Freeze et al. 2001, Sections 2.2 and 2.3).

- **Method 3: Top-Level-Down Elicitation**—Used to develop general event-tree logic diagrams for nominal flow, tectonic processes, igneous activity and Engineered Barrier System (EBS) degradation modes and to provide the basis for identification of some of the project-specific FEPs (SNL 2008c, Section 6.1.1).

- **Method 4: Hybrid Procedures**—Used in the refinement and reclassification of the Nuclear Energy Agency FEPs to make them relevant to the project (Freeze et al. 2001, Section 3).

These FEP identification methods were further applied in connection with analyses supporting the license application. FEP identification for the license application, which built upon the list of 328 FEPs used for the site recommendation (method 1), was performed in phases:

- Refinement of the site recommendation FEP list for consistency with a revised classification scheme and for a more consistent level of detail between FEPs (methods 3 and 4). Implementation of this phase did not change the technical content of the overall FEP list but did result in a minor change in the number of FEPs due to a reorganization and clarification of the applicability and scope of certain FEPs (e.g., whether a near field process was applicable to the in-drift environment or the host rock) (SNL 2008c, Section 6.1.1).

- Identification of potential new FEPs and changes to existing FEPs based on updated or new technical information (e.g., subsequent to the site recommendation) and audits against other recently published international lists. Implementation of this phase resulted in further changes to the overall FEP list, including technical content. Potential FEP changes were evaluated and tracked using a formal FEP configuration management system (SNL 2008c, Section 6.1.1). It should be noted that the Nuclear Energy Agency

International FEP Database was updated in 2006 (NEA 2006a). This update to the Nuclear Energy Agency FEP Database was reviewed for new FEPs. It was determined that the potential FEPs introduced by the two new projects noted in the update presented no additional scope beyond FEPs already addressed in the TSPA FEP list (SNL 2008a, Appendix F).

- A set of alternate FEPs was independently developed for the express purpose of providing an independent list suitable for audit and comparison in support of the demonstration of comprehensiveness of the FEPs list for the license application. The alternate FEPs were developed using a top-down functional analysis of the repository. Each function was subdivided into successively smaller, more-detailed subfunctions until it could be characterized at a level of detail similar to the FEPs list for license application. Therefore, each low-level functional element represented an alternate FEP or a group of related FEPs. A comparison of the FEP list for the license application against the alternate FEP list was made (1) to build confidence that the license application FEP list was complete; and (2) to identify any additional FEPs that might enhance completeness (SNL 2008c, Section 6.1.1).

Additional refinements resulted from continuous iterative reviews and associated brainstorming (method 2) of the FEP list for the license application by subject matter experts.

The combined and iterative use of all four of the FEP identification methods resulted in a comprehensive FEP list for the license application consisting of 374 FEPs (SNL 2008c, Section 6.1) (Table 2.2-1). Table 2.2-1 lists all FEPs potentially relevant to long-term postclosure performance of the repository, organized numerically by FEP number. The table presents the FEP number, FEP name, the feature category (Section 2.2.1.1.2) the FEP is commonly associated with, and the process or event category (Section 2.2.1.1.2) the FEP is associated with.

The numbers used to identify the FEPs all have the form #.#.##.##.0x. The first three groups (#.#.##) are numeric and are based on the hierarchical classification levels in the Nuclear Energy Agency International FEP Database (Safety Assessment Management 1997) and correspond to Nuclear Energy Agency layer, category, and heading (Freeze et al. 2001, Section 3.1). The fourth group is also numeric and is simply a sequential indicator. The final group is alphanumeric with the form.0A,.0B,.0C, and so on. The final group of the FEP number provides traceability back to the site recommendation FEP list (in which the final group of the FEP number was numeric (e.g., .00,.01)). For example, license application FEPs 1.1.02.00.0A (Chemical effects of excavation and construction in EBS) and 1.1.02.00.0B (Mechanical effects of excavation and construction in the EBS) both derive from the FEP list for the site recommendation FEP 1.1.02.00.00 (Excavation/Construction).

In addition to organizing the complete list of FEPs by assigning a unique identification number to each FEP, it is also useful to group related FEPs, as presented in Table 2.2-2. This table has been organized in order of features, with the processes acting within or on the feature, followed by events. The features are listed in order along the likely path that the water takes in reaching the waste, and then the path that the radionuclides take from the repository to the accessible environment. Table 2.2-2 provides traceability back to the barriers, and the features and processes contributing to the capability of the barriers, that were presented in Section 2.1. Because events and processes act on or within features, mapping events to the relevant features potentially affected by the events and processes allows for a check of the completeness of the FEP list.

Several FEPs relate either directly or indirectly to parameters that require either procedural safety controls or design configuration control to ensure the TSPA analysis basis is met and are identified in Table 2.2-3. Table 1.9-9 contains a summary of the parameters that require such controls. Section 2.1 identifies those features of natural barriers and EBS that contribute to barrier performance and evaluates the processes and events that contribute to the capability of the barriers.

In addition to the preclosure parameters being controlled, the Performance Confirmation Program that is presented in Chapter 4 provides information to confirm that natural and engineered systems and components required for repository operation, which are designed or assumed to operate as barriers after permanent closure, are functioning as described in this chapter.

2.2.1.1.2 FEP Classification

Several different general classification schemes can be used to organize FEPs. These are sorting and organizing approaches used to support consistent and multidiscipline analysis of the FEPs. Common classification schemes (NEA 1992, pp. 26 to 28) include by cause, by time scale, by location, by scientific discipline, by radionuclide transfer agent, and by radionuclide mobilization phenomena. Other common classification schemes (NEA 1999, p. 28) include by field of effect, by causative factors, and layered by creating a hierarchical organization in which some classification schemes become subsets of other broader classification schemes. In the early part of the iterative FEP identification and classification process (e.g., to support the TSPA for site recommendation), FEP classification was derived from a Nuclear Energy Agency classification scheme (NEA 1999, pp. 28 to 34; Freeze et al. 2001, Section 3). It was general in nature and was based on a layered combination of several of the common classification schemes. For the license application, a revised classification was developed based on a Yucca Mountain–specific combination of location, fields of effect, radionuclide mobilization phenomena, and causative factors. This classification scheme was further refined and modified based on a mapping of FEPs to the features that comprise the natural and engineered barriers (SNL 2008c, Section 6.1). The use of different classification schemes for the site recommendation performance assessments and the license application performance assessments provides additional confidence in the comprehensiveness of the FEP list.

In general, an event or process acts upon a feature. Therefore, the bases for the FEP classification scheme for the TSPA are two separate mappings: one corresponding to the list of repository-relevant features, the other corresponding to the list of repository-relevant events and processes. The mapping of the FEPs to features and to repository-relevant events and processes is found in Table 2.2-1.

The remainder of this subsection describes the FEP classification scheme and how it facilitates the organization of the FEPs and their disposition within the performance assessment model components presented in Section 2.3:

Features—Section 2.1 identifies the barriers that are comprised of both natural and engineered features. It is these features that are described and used in the classification of FEPs. In addition, the engineering-related features are classified in Section 1.9 as systems, structures, or components.

The repository features contribute to the performance of the repository in various ways. Some of these features contribute to performance of barrier functions, as described in Section 2.1. The barrier functions include preventing the release or substantially reducing the release rate of radionuclides from the waste, or preventing or substantially reducing the rate of movement of water or radionuclides from the repository to the accessible environment.

The principal features of the repository system are identified below. This list includes the features within the barriers plus those features that support the capability of the barrier functions. In addition, this list includes features (notably, the biosphere, backfill, and system) that are necessary to address repository performance or address specific FEPs but do not directly relate to the capability of barriers. With the exception of "system," this list is presented in the order of the feature along the likely path that water takes in reaching the waste and then the path that radionuclides take from the repository to the accessible environment:

- Topography and surficial soils
- Unsaturated zone above the repository
- Backfill/seals
- Emplacement drifts
- Drip shield
- Waste package
- Waste form and waste package internals
- Waste package pallet
- Invert
- Unsaturated zone below the repository
- Saturated zone
- Biosphere
- System.

A category termed "system" has also been included to address FEPs that are potentially relevant to the repository system as a whole (SNL 2008c, Section 6.1.3). The included systems FEPs are summarized in Table 2.2-4. The biosphere feature is necessary to address repository performance but is not related to the capability of any of the barriers. As described in Section 1.3.6, repository backfill is limited to the openings that connect the emplacement areas to the surface, mainly the ramps and shafts and not the emplacement drifts themselves.

The FEPs related to the engineered features of the EBS (emplacement drifts, drip shields, waste packages, waste forms and waste package internals, waste package pallet and invert) include a wide range of degradation, deterioration, and alteration processes as called for in proposed 10 CFR 63.114(a)(6). These FEPs are identified in Tables 2.2-1 and 2.2-2. These degradation, deterioration, and alteration processes have been categorized as being either chemical/thermal-chemical, mechanical/thermal-mechanical, radiological, microbiological, or induced by seismic or igneous events. The inclusion or exclusion of these processes acting on the engineered features of the EBS, as well as the effects of disruptive events on the degradation, deterioration, and alteration of these features, is identified in these tables. The basis for the exclusion of these degradation, deterioration, or alteration processes or the approach for inclusion of these processes is identified in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008a). Note that, as described in Section 1.3.6, backfill is not considered a feature of the EBS and is not used in the emplacement drifts.

Processes—Processes and events both act on or within features. The processes are grouped as follows:

- Hydrologic and thermal-hydrologic
- Chemical and thermal-chemical
- Mechanical and thermal-mechanical
- Microbiological
- Radiological
- Transport
- Characteristics.

Hydrologic flow processes include climate change, precipitation, infiltration, runoff, unsaturated zone flow, flow diversion, capillarity, matrix imbibition, evaporation, condensation, and saturated zone flow. These flow processes are evaluated using models that are described in Sections 2.3.1, 2.3.2, 2.3.3, 2.3.5, 2.3.7, and 2.3.9.

Chemical processes include the geochemical environment and a range of chemical processes that affect the degradation mechanisms of engineered features. These chemical processes include such detailed processes as dissolution, precipitation, oxidation, salt deliquescence, general corrosion, localized (or crevice) corrosion, alteration, and solubility. The chemical processes included in model abstractions are presented in Sections 2.3.5, 2.3.6, 2.3.7, 2.3.8, 2.3.9, and 2.3.11.

Mechanical processes include drift degradation and a range of mechanical processes that affect the degradation of engineered features. These mechanical processes include rockfall, drift collapse, stress corrosion cracking, hydrogen embrittlement, buckling, and floor heave, among others. The drift degradation and mechanical degradation processes included in model abstractions for the engineered features are presented in Sections 2.3.4, 2.3.6, 2.3.7, and 2.3.11.

Thermal processes may affect the hydrologic (e.g., flow), chemical, and mechanical environments. The radioactive wastes to be placed in the repository give off varying amounts of heat at the time they will be emplaced. Even though the heat flux decreases with time, certain effects of heat will be present after repository closure. The thermal processes include conduction, radiation, and convection. These thermal process effects on flow are through evaporation, condensation, and vapor flow. The thermal effects on chemistry are through evaporation, mineral precipitation, dissolution, and on thermal-chemical properties. The thermal effects on the mechanical environment are through thermal stresses and corresponding effects on rock mass strength and degradation. The thermal processes included in model abstractions are presented in Sections 2.3.3, 2.3.4, 2.3.5, and 2.3.11.

In general, for the purposes of FEP analysis, thermal processes are not treated in isolation but instead are coupled with the process that is affected by thermal conditions. For example, the processes will be generally referred to as thermal-hydrologic, thermal-chemical, or thermal-mechanical to indicate the principal couplings considered. The convention used to describe coupled processes places the principal causing process first and the affected process second. For example, thermal-chemical processes are those in which the thermal environment affects the projection of the chemical environment. Generally, the reverse coupling (in this example, the effect of chemistry change on the thermal environment) is significantly weaker than the forward coupling (SNL 2008c, Section 6.1.3).

Microbiological processes include the potential effects of microorganisms on other processes relevant to performance, such as microbial effects on chemistry. Microbiological processes included in model abstractions are presented in Section 2.3.6.

Radiological processes include the potential effects of ionizing radiation resulting from the decay of radioactive materials on other processes potentially relevant to performance, such as chemistry. Specific radiological processes include radiolysis. As in the case of thermal effects, the radiological processes are generally addressed through their coupling with other processes that in turn could potentially affect repository performance. Radiological processes also include radiological exposure to the reasonably maximally exposed individual (RMEI) and the resulting doses. The radiological processes included in model abstractions are presented in Section 2.3.10.

Transport processes include such processes as advection, diffusion, dispersion, matrix diffusion, retardation, and colloid filtration. These processes occur within the EBS and the Lower Natural Barrier, as defined in Section 2.1. Models used to evaluate these transport processes are described in Sections 2.3.7, 2.3.8, and 2.3.9. Transport of radionuclides through various biosphere pathways to the RMEI is described in Section 2.3.10. In addition, radionuclide transport following an eruptive volcanic event is described in Section 2.3.11.

Processes also include "characteristics" that are not physical-chemical-biological processes but are properties of the features that need to be evaluated for their inclusion in abstraction models of the processes and events. For example, tectonic processes are included in the characteristics category. In addition, a number of FEPs relate to geologic characteristics of the features (e.g., fractures or faults).

In the EBS specific processes were typically addressed with a separate FEP for each potentially affected EBS component, whereas more general processes were addressed with a single FEP. For example, FEPs 2.1.03.01.0B (General corrosion of drip shields), 2.1.03.01.0A (General corrosion of waste packages), and 2.1.02.13.0A (General corrosion of cladding) relate to the same degradation process applied to three different features of the EBS. FEP 2.1.09.24.0A (Diffusion of colloids in EBS) may potentially affect radionuclide transport from the waste form and waste package internals to the invert and therefore is evaluated in these two features of the EBS.

Similarly, in the natural system, specific processes were typically addressed with a separate FEP for each component of potential interest (e.g., the unsaturated zone, saturated zone, surficial soils), whereas more general processes were addressed with a single FEP. For example, FEPs 2.2.07.15.0B (Advection and dispersion in the unsaturated zone) and 2.2.07.15.0A (Advection and dispersion in the saturated zone) relate to the same radionuclide transport processes applied to two different features of the Lower Natural Barrier. FEP 2.2.07.02.0A (Unsaturated groundwater flow in the geosphere) is applicable to both the unsaturated zone above the repository and the unsaturated zone below the repository.

To ensure completeness, some FEPs are repeated multiple times in different rows of Table 2.2-1. This repetition is because a process or event FEP applies to more than one feature. For completeness and enhanced traceability, the repetition of the FEP across different features assures that the FEP, if included, is included consistently in the different features and, if the FEP is excluded, all relevant features related to the FEP have been evaluated.

For example, FEP 1.3.01.00.0A (Climate change) is applicable in the following features: topography and surficial soils, the unsaturated zone above the repository, the unsaturated zone below the repository, and the saturated zone. Therefore, this FEP is repeated four times in Table 2.2-1 and occurs in four different locations (for the four different features identified above) in Table 2.2-2.

The repetition of FEPs across the different relevant features also allows a more traceable evaluation of the inclusion of these FEPs in the different model abstraction areas presented in Section 2.3. For example, fractures (FEP 1.2.02.01.0A) are included in the assessment of the processes affecting infiltration through the topography and surficial soils presented in Section 2.3.1, unsaturated flow in the unsaturated zone above the repository presented in Section 2.3.2, flow diversion around the emplacement drifts in the unsaturated zone above the repository presented in Section 2.3.3, mechanical degradation of the EBS presented in Section 2.3.4, thermal-hydrologic and thermal-chemical environment in the unsaturated zone above the repository presented in Section 2.3.5, transport through the unsaturated zone below the repository presented in Section 2.3.8, and flow and transport through the saturated zone presented in Section 2.3.9.

Events—Processes and events both act on or within features. The relevant events are grouped as follows:

- Seismic
- Criticality
- Igneous
- Human intrusion
- Early failure.

Each of the above events meets the definition of an event in NUREG-1804 in that if they occur, they occur during an interval that is short compared to the period of performance.

A particular event may affect multiple features of the repository system. As a result, the same event may be repeated several times in Tables 2.2-1 and 2.2-2 to address all relevant features potentially affected by a particular event. This repetition assists in ensuring that all relevant features that are potentially affected by a particular event have been evaluated for significance to the performance assessment. For example, FEP 2.2.06.01.0A (Seismic activity changes porosity and permeability of rock) is potentially relevant to the unsaturated zone above the repository, the unsaturated zone below the repository, and the saturated zone. Similarly, FEP 1.2.04.04.0A (Igneous intrusion interacts with EBS components) may potentially affect all of the EBS features contacted by the unlikely intrusion event, such as the intersected emplacement drifts, the drip shields, the waste packages, the cladding, and the waste form and waste package internals.

The general process of igneous or seismic activity is not relevant to postclosure repository performance, but the occurrence of a discrete event of sufficient magnitude and proximity to affect the other processes that nominally occur during the 10,000 year period after closure is relevant. As discussed in Section 2.2.2.1, seismic events must have a sufficient magnitude (in terms of peak ground velocity or peak ground acceleration) to have any significant effect on repository performance. Similarly, as discussed in Section 2.2.2.2, igneous events must intersect the repository block to have any significant effect on repository performance.

The potential for criticality events is determined by a number of precursor conditions that must occur for the inventory to achieve a potentially critical configuration. These conditions include reduced neutron absorber material and the presence of neutron reflectors and neutron moderators (such as water). Section 2.2.1.4.1 presents the evaluation of the Criticality Event Class.

An early failure is defined as the through-wall penetration of a waste package or drip shield due to manufacturing- or handling-induced defects, at a time earlier than would be predicted by mechanistic degradation models for a defect-free waste package or drip shield. Early Failure Events are described in Section 2.2.2.3 and Section 2.3.6.

As specified in proposed 10 CFR 63.321, the criteria under which human intrusion must be evaluated are based on determining the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers. The bases for the timing of the human intrusion event are presented in Section 2.4.

Once an event occurs, the hydrologic and thermal-hydrologic, chemical and thermal-chemical, mechanical and thermal-mechanical, microbiological, radiological, and transport processes that nominally occur in the repository system may be modified. For example, the presence of magma in the drift, which could occur following an igneous event, would affect the thermal and chemical environments in the drift, which in turn would affect the degradation processes of the EBS and its features. In addition, an eruptive igneous event would change the radionuclide transport pathway from being dominated by aqueous processes (groundwater flow and transport) to being dominated by atmospheric transport and subsequent redistribution. Similarly, the occurrence of an earthquake of sufficient magnitude to affect the mechanical environment in the drift is likely to affect the thermal environment and the degradation processes of the EBS and its features. The processes that are expected to be affected by such a seismic event are discussed in Section 2.3.4. The processes that are expected to be affected by an unlikely igneous event are discussed in Section 2.3.11.

The above discussion describes the overall categorization of Yucca Mountain FEPs. As described, processes and events act on or within individual features. Table 2.2-1 correlates (1) processes with the features in which these processes are operative and (2) events with the features that are potentially affected by the occurrence of the event. The individual FEPs (e.g., the FEP list resulting from the FEP identification process described in Section 2.2.1.1.1) are presented in

Table 2.2-5. References to the appropriate subsection of Section 2.3 where included processes are discussed are also indicated where appropriate.

- Topography and surficial soils (Section 2.3.1)
- Unsaturated zone above the repository (Sections 2.3.2, 2.3.3, and 2.3.5)
- Emplacement drift (Sections 2.3.5 and 2.3.7)
- Backfill/seals (as described in Section 1.3.6, backfill is not included in the emplacement drifts and is therefore not considered further in the performance assessments)
- Drip shield (Sections 2.3.6 and 2.3.7)
- Waste package (Sections 2.3.6 and 2.3.7)
- Cladding (Section 2.3.7)
- Waste form and waste package internals (Section 2.3.7)
- Pallet (Section 2.3.4)
- Invert (Section 2.3.7)
- Unsaturated zone below the repository (Section 2.3.8)
- Saturated zone (Section 2.3.9)
- Biosphere (Section 2.3.10)
- System (Table 2.2-4)
- Igneous (Section 2.3.11)
- Seismic (Section 2.3.4)
- Criticality (Section 2.2.1.4.1)
- Human intrusion (Table 2.2-6 and Section 2.4).

The tables have been organized in this fashion because (1) multiple processes may act on or within individual features, (2) events generally cut across multiple features, and (3) the subsections of the model abstraction, which is discussed in Section 2.3, are generally arranged by features and then events (an exception is the seismic events that are discussed in Section 2.3.4 with other related mechanical degradation processes). These tables thus provide a comprehensive list of FEPs having the potential to affect the performance of the repository system. This list considers the possible modes of degradation, deterioration, and alteration of engineered features, whether caused by hydrologic and thermal-hydrologic, chemical and thermal-chemical, mechanical and thermal-mechanical, microbiological, radiological, and transport processes or igneous, seismic, criticality, or human intrusion events.

2.2.1.2 Screening of FEPs

[NUREG-1804, Section 2.2.1.2.1.3: AC 2; Section 2.2.1.3.3.3: AC 2(5); Section 2.2.1.3.4.3: AC 3(7)]

In Step 2 of the FEP analysis and scenario development process (Section 2.2.1.1), the list of FEPs identified and classified in Step 1 was analyzed to determine (1) which FEPs should be included in the performance assessment compliance analyses, and (2) which should be excluded. A FEP is included or excluded based on any one or more of the following FEP screening criteria (Figure 2.2-1):

Low Probability Criteria—Proposed 10 CFR 63.114(a)(4) requires any performance assessment used to demonstrate compliance with 63.113 for 10,000 years after disposal to "Consider only features, events, and processes consistent with the limits on performance assessment specified at 63.342." Proposed 10 CFR 63.342(a) requires "DOE's performance assessments conducted to show compliance with 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, and processes, i.e., those that are estimated to have less than one chance in 10,000 of occurrence within 10,000 years of disposal (less than one chance in 100,000,000 per year)" (70 FR 53313, pp. 53319 to 53320). In other words, very unlikely events have a frequency of occurring of less than 10^{-8} per year. Thus, very unlikely FEPs can be excluded (screened out) from the performance assessment to show compliance with the individual protection standards for the 10,000 years following disposal on the basis of low probability.

The low probability screening criterion has been applied in the FEP screening process to screen events that meet the quantitative threshold identified in proposed 10 CFR 63.342(a) associated with demonstrating compliance with the individual protection standards for permanent closure and human intrusion, and the groundwater protection standards for the 10,000 years following disposal. When the probability screening criterion is applied to events that have a probability distribution, the mean of the distribution range is used to determine if the event will be included or excluded from the performance assessment.

In demonstrations of compliance with the groundwater protection standards and the individual protection standard for human intrusion, proposed 10 CFR 63.342(b) requires "For performance assessments conducted to show compliance with 63.321(b) and 63.331, DOE's performance assessments shall exclude the unlikely features, events, and processes, or sequences of events and processes, i.e., those that are estimated to have less than one chance in 10 and at least one chance in 10,000 of occurring within 10,000 years of disposal (less than one chance in 100,000 per year and at least one chance in 100,000,000 per year)." The exclusion of unlikely FEPs from the performance assessments conducted to show compliance with the groundwater protection standards and the individual protection standard for human intrusion occurs in the process of developing the implementation of relevant scenario classes for the assessments described in Section 2.2.1.3, below, and presented in Section 2.4.4. Exclusion of unlikely FEPs is achieved by including only those initiating events in a scenario class with exceedance frequencies greater than 10^{-5} per year. The term "initiating event" as used in Section 2.2 refers to early failure, seismic, and igneous events that are incorporated into various scenario classes used for postclosure performance assessment.

Low Consequence Criteria—Pursuant to proposed 10 CFR 63.114(a)(5) and (a)(6), any performance assessment used to demonstrate compliance with 10 CFR 63.113 for 10,000 years after disposal must:

> (a)(5) Provide the technical basis for either inclusion or exclusion of specific features, events, and processes in the performance assessment. Specific features, events, and processes must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, for 10,000 years after disposal, would be significantly changed by their omission.
>
> (a)(6) Provide the technical basis for either inclusion or exclusion of degradation, deterioration, or alteration processes of engineered barriers in the performance assessment, including those processes that would adversely affect the performance of natural barriers. Degradation, deterioration, or alteration processes of engineered barriers must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual or radionuclide releases to the accessible environment, for 10,000 years after disposal, would be significantly changed by their omission.

Accordingly, to the extent that a particular FEP has no significant effect on radiological exposure, or radionuclide release, or on an intermediate-performance measure that can be linked to radiological exposure or radionuclide release, that FEP can be excluded (screened out) from the performance assessment on the basis of low consequence. FEP screening may include assessing both the likelihood of the FEP occurring and the potential consequences of the FEP were it to occur because, consistent with the definition of a performance assessment (proposed 10 CFR 63.2), both aspects enter into the evaluation of radiological exposure to the RMEI and radionuclide releases to the accessible environment.

Finally, having established the criterion for excluding very unlikely FEPs, proposed 10 CFR 63.342(a) states in part, "DOE's performance assessments need not evaluate the impacts resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurrence if the results of the performance assessments would not be changed significantly in the initial 10,000 year period after disposal" (70 FR 53313, pp. 53319 to 53320). Not changing the results of the performance assessment is equivalent to stating that the combined effects of (1) the low likelihood of the FEP existing given the characteristics of the Yucca Mountain site and the repository design and (2) the low consequences of the FEP on repository performance even in the unexpected case that the FEP did exist are sufficient to demonstrate that the FEP will have no significant impact on the predicted dose in the TSPA.

For some of the FEPs, it was estimated that the probability of the condition, event, or process occurring during the initial 10,000 years after disposal was extremely low. However, it was not possible to provide a sufficiently detailed quantification of the probability to justify its exclusion based solely on the low-probability criterion, given the current state of knowledge of data and models and the uncertainty associated with calculating FEP probabilities for a 10,000 year period. In these cases, a qualitative evaluation of the consequence was made, taking into account the fact that the FEP is not expected to occur. This evaluation includes consideration of expected antecedent conditions that would be necessary for the FEP to impact repository performance and represents a risk-informed approach that examines the joint outcome of the probability and the consequence of such FEPs. If these risk-informed evaluations indicated an insignificant impact on the results of a performance assessment (or on an intermediate performance measure), then the FEP was excluded based on low consequence. This is consistent with the definition of performance assessment in proposed 10 CFR 63.2, which requires that the consequences of all significant FEPs (i.e., “the dose incurred by the RMEI”) be “weighted by their probability of occurrence.”

Regulation—Some FEPs may be specifically excluded by regulations that limit the scope of analysis to specific characteristics, concepts, and definitions (NUREG-1804, Section 2.2.1.2.1.3, Acceptance Criterion 2). The regulatory requirements most commonly used for screening FEPs include the characteristics, concepts, and definitions pertaining to the reference biosphere, geologic setting, and the RMEI (SNL 2008c, Section 6.2). FEP 1.4.08.00.0A, Social and institutional developments, is an example of a FEP that is excluded on the basis of regulation.

Regulations require inclusion of certain FEPs in performance assessments that are conducted to demonstrate compliance with the individual protection standards for the period after 10,000 years after disposal, but within the period of geologic stability. In particular, proposed 10 CFR 63.342(c) requires:

> (c) For performance assessments conducted to show compliance with 63.311(a)(2) and 63.321(b)(2), DOE’s performance assessments shall project the continued effects of the features, events, and processes included in paragraph (a) of this section beyond the 10,000 year post-disposal period through the period of geologic stability. DOE must evaluate all of the features, events, or processes included in paragraph (a) of this section, and also:
>
> (1) DOE must assess the effects of seismic and igneous scenarios subject to the probability limits in paragraph (a) of this section for very unlikely features, events, and processes. Performance assessments conducted to show compliance with 63.321(b)(2) are also subject to the probability limits in paragraph (b) of this section for unlikely features, events, and processes.
>
> (i) The seismic analysis may be limited to the effects caused by damage to the drifts in the repository and failure of the waste package.
>
> (ii) The igneous analysis may be limited to the effects of a volcanic event directly intersecting the repository. The igneous event may be limited to that causing damage to the waste packages directly, causing releases of radionuclides to the biosphere, atmosphere, or groundwater.

> (2) DOE must assess the effects of climate change. The climate change analysis may be limited to the effects of increased water flow through the repository as a result of climate change, and the resulting transport and release of radionuclides to the accessible environment. The nature and degree of climate change may be represented by constant climate conditions. The analysis may commence at 10,000 years after disposal and shall extend to the period of geologic stability. The constant value to be used to represent climate change is to be based on a log-uniform probability distribution for deep percolation rates from 13 to 64 mm/year (0.5 to 2.5 inches/year).
>
> (3) DOE must assess the effects of general corrosion on the engineered barriers. DOE may use a constant representative corrosion rate throughout the period of geologic stability or a distribution of corrosion rates correlated to other repository parameters (70 FR 53313, pp. 53319 to 53320).

FEPs associated with the requirements above have been evaluated for inclusion in the appropriate performance assessments. No changes to screening decisions were necessary to address the inclusion of FEPs specified by proposed 10 CFR 63.342(c) (1), (2), and (3). In other words, FEPs that are required by regulation to be included in the performance assessments for the period after the first 10,000 years following disposal, but within the period of geologic stability, are also included in the performance assessments for the 10,000 years after disposal. Further, FEPs that are excluded from the performance assessments for the 10,000 years after disposal remain excluded in the performance assessments for the period after the first 10,000 years after disposal, but within the period of geologic stability.

Specifically, the following included FEPs address proposed 10 CFR 63.342(c)(1)(i):

- 1.2.02.03.0A, *Fault Displacement Damages EBS Components*
- 1.2.03.02.0A, *Seismic Ground Motion Damages EBS Components*
- 1.2.03.02.0C, *Seismic-induced Drift Collapse Damages EBS Components*
- 1.2.03.02.0D, *Seismic-induced Drift Collapse Alters In-drift Thermal-hydrology*
- 1.2.03.03.0A, *Seismicity Associated with Igneous Activity.*

Additionally, excluded FEP 1.2.03.02.0B, Seismic Induced Rockfall Damages EBS Components, was evaluated with respect to proposed 10 CFR 63.342(c)(1)(i). This FEP is excluded from the performance assessments for the period after 10,000 years following disposal, but within the period of geologic stability on the basis of low consequence. The details of this evaluation can be found in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008a, Section 6).

The following included FEPs address proposed 10 CFR63.342(c)(1)(ii):

- 1.2.04.03.0A, *Igneous Intrusion into Repository*
- 1.2.04.04.0A, *Igneous Intrusion Interacts with EBS Components*
- 1.2.04.04.0B, *Chemical Effects of Magma and Magmatic Volatiles*
- 1.2.04.06.0A, *Eruptive Conduit to Surface Intersects Repository*

- 1.2.04.07.0A, *Ashfall*
- 1.2.04.07.0C, *Ash Redistribution Via Soil and Sediment Transport*.

The following included FEPs address proposed 10 CFR63.342(c)(2):

- 1.4.01.01.0A, *Climate Modification Increases Recharge*
- 2.3.11.03.0A, *Infiltration and Recharge*
- 1.3.01.00.0A, *Climate Change*.

The following included FEPs address proposed 10 CFR63.342(c)(3):

- 2.1.03.01.0A, *General Corrosion of Waste Packages*
- 2.1.03.01.0B, *General Corrosion of Drip Shields*.

Each FEP has been analyzed for inclusion or exclusion from the postclosure performance assessments conducted to demonstrate compliance with proposed 10 CFR 63.311, proposed 10 CFR 63.321, and 10 CFR 63.331.

The individual FEPs (e.g., the FEP List resulting from the FEP identification and classification processes described in Sections 2.2.1.1.1 and 2.2.1.1.2) are presented in Table 2.2-5. Table 2.2-5 provides a comprehensive list of FEPs having the potential to affect the performance of the repository system. The list includes FEPs that address the possible modes of degradation, deterioration, and alteration of engineered features, whether caused by mechanical, thermal, chemical, hydrologic, radiological, or microbiological processes, or igneous, seismic, criticality, or human intrusion events.

Table 2.2-5 provides the FEP number, FEP name, a description of the FEP, and the inclusion or exclusion screening decision for each FEP. For excluded FEPs, the screening decision identifies the criteria used for screening (probability, low consequence, or regulatory). The screening decision for included FEPs indicates the specific compliance demonstrations (proposed 10 CFR 63.311, proposed 10 CFR 63.321, or 10 CFR 63.331) that include the FEP.

It is evident from Tables 2.2-1, 2.2-2, 2.2-5, and 2.2-7 that several FEPs apply to multiple features of the natural barriers and the EBS. Two FEPs in particular warrant explicit discussion because they relate to all postclosure relevant aspects of the repository design. Included FEP 1.1.07.00.0A, Repository design, specifies that the performance assessment must account for the design features and material characteristics. Excluded FEP 1.1.08.00.0A, Inadequate quality control and deviations from design, relates to the potential effects of inadequate quality assurance and control procedures and inadequate testing during the design, construction, and operation of the repository. Lack of quality control could result in a poorly designed repository, unmodeled design features, deviations from design, material defects, faulty waste package fabrication, and faulty or nondesign standard construction. These two FEPs relate to how the design of the repository is evaluated and analyzed in performance assessment and are discussed below.

The repository design presented in SAR Section 1 (principally SAR Sections 1.3 and 1.5) is the basis for the performance assessment, therefore FEP 1.1.07.00.0A is included. The inclusion of the repository design is accomplished through analyses of individual FEPs that are either excluded or included based on that design. The structures, systems and components of the repository design that are relevant to the features of the natural barriers and the EBS used in performance assessment are identified in Table 1.9-9. Table 1.9-9 also presents the design control parameters that, along with other requirements and performance specifications, describe the bases for the repository design. These design control parameters, as well as the resulting design based on these control parameters, have been used as the basis to exclude or include repository design related FEPs. A mapping of representative FEPs relying on those control parameters is contained in Table 2.2-3. That is, Table 2.2-3 depicts how the repository design has been used in the performance assessment. It is relevant to note that in some cases the repository design has been used to exclude certain FEPs while in other cases the repository design has been included as part of the initial or boundary conditions in models and analyses that are abstracted in the TSPA model. The last column in Table 2.2-3 indicates where FEPs relying on the repository design and associated control parameters are discussed in various postclosure SAR sections.

A FEP related to the included FEP 1.1.07.00.0A, Repository design, is the excluded FEP 1.1.08.00.0A, Inadequate quality control and deviations from design. If there are inadequate quality controls or significant deviations from the design that result from inadequate quality control, it is possible to significantly affect the analyzed conditions. Recognizing this, as described in Section 1.9.3, the management systems for operation of the repository include administrative and procedural safety controls. The establishment of adequate administrative and procedural safety controls ensure operations are within analyzed conditions of the postclosure safety assessment and TSPA. The development of these systems is described in Section 5.

The technical bases for the screening decisions are covered in detail in the *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008a).

2.2.1.3 Event Class and Scenario Class Formation
[NUREG-1804, Section 2.2.1.2.1.3: AC 3]

As noted in Section 2.2.1 above, Step 3 in the analysis of FEPs and scenarios is the aggregation of FEPs into Event Classes or Scenario Classes for the purpose of further screening or analyses. The concept of an event class is introduced in 10 CFR 63.102(j) as "An event class consists of all possible specific initiating events that are caused by a common natural process (e.g., the event class for seismicity includes the range of credible earthquakes for the Yucca Mountain site)." For the purposes of analyses, event classes need not be limited to aggregation of initiating events by a common natural process; event classes can be the aggregation of initiating events by any common characteristic. For example, criticality events are aggregated into the Criticality Event Class and early waste package failures and early drip shield failures are aggregated into the early failure event class. Event classes are the most basic type of scenario class, with common characteristics that can be usefully aggregated for the purposes of screening or analysis. The objective of scenario class development for TSPA is to define a limited set of scenario classes that could reasonably be analyzed quantitatively while still maintaining comprehensive coverage of the range of possible future states of the repository system (SNL 2008c, Section 6.3). There is an essentially infinite number of possible future states, and for scenario development to be useful, it must generate scenario classes that are representative of the range of futures that are potentially relevant to the licensing of the facility and fit into a computational structure amenable for consequence analyses. Scenario formation forms a link between the list of FEPs and the modeling and consequence calculations (SNL 2008c, Section 6.3). Therefore, scenario class formation is influenced by the types of models and calculation tools available (NEA 1992, p. 52) as well as the kinds of FEPs under consideration.

The FEP classification structure described in Section 2.2.1.1 that makes use of two separate mappings—one corresponding to the list of repository-relevant features, the other corresponding to the list of repository-relevant events and processes—readily provides a framework for organizing scenario development and assessment. The mapping of the FEPs to features and to repository-relevant events and processes is found in Tables 2.2-1 and 2.2-2. The feature list in Table 2.2-2 is presented in the order of the feature along the likely path that water takes in reaching the waste, and then the path that radionuclides take from the repository to the accessible environment. The grouping of the included FEPs in the order of features along the likely path of the movement of water through the system provides a logical sequence for connecting FEPs for scenario formation. This grouping also ensures that all repository relevant features are considered in each scenario. This classification structure approximates the way the repository system is conceptualized, and the order that information flows within the TSPA model. The mapping of FEPs to repository processes and events also assists in scenario development and analysis. Those retained FEPs that are mapped to processes will generally occur in all scenarios.

For the purpose of scenario class formation, the features and nominal processes generally exist and occur for all possible repository futures, while specific events may or may not occur in the range of possible future states of the repository system (events have an aleatory component). This conceptualization allows the full set of possible repository futures to be subdivided into possible futures that have events and futures that have no events. This is one reason why scenario class formation is based upon the retained events while the features and processes are generally applicable across all scenario classes. Therefore, the repository features identified in Section 1.9 and 2.1 and listed in Section 2.2.1.1.2 and the processes listed in Section 2.2.1.1.2 are part of every possible repository future to varying degrees; they belong to all scenario classes. In this sense, the retained features and processes may be thought of as nominal; this is not the same as thinking of retained features and processes as equivalent to a nominal scenario class.

2.2.1.3.1 Scenario Class Formation Considering Individual Protection and Groundwater Protection Standards

Based on the probabilities described in Section 2.2.2, the three retained events that have been identified for inclusion in the performance assessments to demonstrate compliance with proposed 10 CFR 63.311 are:

- Seismic
- Igneous
- Early waste package and drip shield failure.

These three event classes are independent of each other and are not mutually exclusive. In other words, the occurrence or nonoccurrence of one event class has no effect on the probability of occurrence of the other event classes and the occurrence of one event does not preclude the occurrence of the other events. For example, it is possible to conceive of a repository future in which an early failure occurs and a seismic event occurs. On the other hand, any repository future that contains a seismic event or an early failure is, by definition, mutually exclusive of repository futures that have no events. This is represented conceptually by the Venn Diagram in Figure 2.2-2. In Figure 2.2-2, the full set of repository futures is represented by the area within the large rectangle. The area inside circle I represents those futures with one or more igneous events (which may or may not also include seismic and early failure events), the area inside circle S represents those futures with one or more seismic events (which may or may not also include igneous events and early failure events), and the area inside the rectangle EF represents the futures with one or more early failure events (which may or may not also include igneous events and seismic events). The area outside the combined area of I, S, and EF represents futures with no events. The fact that the areas of I, S, and EF overlap represents that these events are not mutually exclusive (SNL 2008c, Section 6.3).

It is possible to divide the full set of repository futures into subsets that are mutually exclusive in the following manner:

Starting from the list of retained event classes sets of mutually exclusive futures with the three preceding types of events are defined. These are listed below:

Igneous scenario set, S_I—The set of futures each of which includes one or more igneous events, but no seismic or early-failure events, and also includes retained nominal features and processes.

Seismic scenario set, S_S—The set of futures each of which includes one or more seismic events, but no igneous or early-failure events, and also includes retained nominal features and processes.

Early-failure scenario set, S_{EF}—The set of futures each of which includes one or more early-failure events (i.e., one or more early-failed waste packages and/or one or more early-failed drip shields), but no seismic or igneous events, and also includes nominal features and processes.

The above three sets of futures do not address the complication stemming from the fact that the three events that they are based upon are independent. Other sets of futures must be defined which represent futures that include intersections of the three types of events. Thus, four additional sets of futures are necessary to address the sample spaces representing the repository futures where the occurrence of the three independent events may intersect each other:

Igneous/seismic scenario set, S_{I+S}—The set of futures each of which includes one or more igneous events and one or more seismic events, but no early failure events, and also includes nominal features and processes.

Igneous/early-failure scenario set, S_{I+EF}—The set of futures each of which includes one or more igneous events and one or more early-failure events, but no seismic events, and also includes nominal features and processes.

Seismic/early-failure scenario set, S_{S+EF}—The set of futures each of which includes one or more seismic events and one or more early-failure events, but no igneous events, and also includes nominal waste package and drip shield corrosion/degradation processes.

Igneous/seismic/early-failure scenario set, S_I+$_S$+$_{EF}$—The set of futures each of which includes one or more igneous events and one or more seismic events and one or more early-failure events, and also includes nominal features and processes

One more set of futures is needed to ensure comprehensive coverage of the range of possible future states of the repository system. The possibility that no events occur must also be considered. This additional set of futures is mathematically defined as the complement of the combination of the scenario classes above.

Nominal scenario set, S_N—The set of futures that include nominal features and processes (e.g., corrosion processes, such as general corrosion, localized corrosion, and stress corrosion cracking) but no events (i.e., no igneous and no seismic events and no early waste package or drip shield failures).

The eight sets of futures defined above partition the set of all futures of the repository into a collection of disjoint sets (SNL 2008c, Section 6.3). Figure 2.2-3 is a Venn Diagram representing the eight mutually exclusive sets. Because the union of the eight sets equals all possible futures of the repository as represented by the Venn Diagram in Figure 2.2-3, and the eight sets are disjoint, the probabilities associated with each of the eight sets sum to exactly one.

Note that formation of subsets of repository futures in this manner:

- Relies only on retained events from the initial FEPs screening but requires no specific knowledge of the probability of the events; probabilities of subsets of repository futures defined in this manner are not the same as the probability of the initiating event of the same name.

- Requires no knowledge of the time of occurrence of any initiating event.

These eight sets form a collection of scenario classes in and of themselves (SNL 2008c, Section 6.3). Total expected annual dose could be calculated separately from these eight scenario classes and then combined appropriately to estimate performance. However, as noted previously, scenario class formation is influenced by the types of models and calculational tools available as well as the FEPs that are of interest. For example, proposed 10 CFR 63.342(c) states in part:

> (1) DOE must assess the effects of seismic and igneous scenarios subject to the probability limits in proposed 10 CFR 63.342(a) for very unlikely features, events, and processes. Performance assessments conducted to show compliance with proposed 10 CFR 63.321(b)(2) are also subject to the probability limits in proposed 10 CFR 63.342(b) for unlikely features, events, and processes.
>
> (i) The seismic analysis may be limited to the effects caused by damage to the drifts in the repository and failure of the waste package.
>
> (ii) The igneous analysis may be limited to the effects of a volcanic event directly intersecting the repository. The igneous event may be limited to that

causing damage to the waste packages directly, causing releases of radionuclides to the biosphere, atmosphere, or groundwater.

Additionally, the computational burden for the performance assessments can be unnecessarily increased by a large number of scenario classes. Thus, it is useful to form scenario classes with consideration of these requirements. With some additional knowledge about the probabilities of the events, an understanding of relative amount of damage to the EBS caused by the events, and cautious but reasonable assumptions regarding the timing of the events with respect to each other, some simplifications can be made that allow the eight sets of repository futures above to be further aggregated into primary scenario classes for the purposes of calculation and analyses. The details of the simplifications are described in Section 2.4.2.1.

These simplifications lead to the aggregation of the eight mutually exclusive sets above into four primary scenario classes:

Early-failure scenario class, A_{EF}—The set of futures each of which includes one or more early-failure events (i.e., one or more early-failed waste packages and/or one or more early-failed drip shields).

Igneous scenario class, A_I—The set of futures each of which includes one or more igneous events.

Seismic scenario class, A_S—The set of futures each of which includes one or more seismic events.

Nominal scenario class, A_N—The set of futures that include nominal features and processes (e.g., corrosion processes, such as general corrosion, localized corrosion, and stress corrosion cracking), which is part of the fifth step of scenario analysis outlined in Section 2.2.1, but no initiating events (i.e., no igneous and no seismic events and no early waste package or drip shield failures) (SNL 2008b, Section 6.1).

The details of how the probabilities of the scenario classes and the timing of the scenario class initiating events are handled when computing dose consequences are described in Section 2.4.2.1. The Nominal, Early Failure, Igneous, and Seismic Scenario Classes and the underlying included FEPs are represented using models that describe the evolution of the repository system as well as the degradation, deterioration, and alteration of the engineered features. The models used to describe the included FEPs, as well as the data and parameters used in the abstraction of the model results for purposes of analyzing barrier capability and system performance, are presented in Section 2.3. Table 2.2-5 identifies where each included FEP is presented in each subsection of Section 2.3 to facilitate a review of how the FEP is included in the performance assessments. A special group of included FEPs that are part of all four scenario classes is also included in the TSPA. These are included system FEPs that address global assumptions or bases that the TSPA uses for all calculations and scenario classes. A discussion of these system FEPs is included in Table 2.2-4.

2.2.1.3.2 Scenario Class Formation For the Human Intrusion Standard

Unlike the Early Failure, Seismic, and Igneous Events that are retained based on probabilities that are greater than one chance in 10,000 of occurring within 10,000 years of disposal, the Human Intrusion Event is retained based on regulatory specification to be used by DOE to evaluate the resilience of a geologic repository at the Yucca Mountain site.

Human intrusion scenario—10 CFR 63.322 states "For the purposes of the analysis of human intrusion, DOE must make the following assumptions:

a. There is a single human intrusion as a result of exploratory drilling for groundwater;

b. The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository;

c. The drillers use the common techniques and practices that are currently employed in exploratory drilling for groundwater in the region surrounding Yucca Mountain;

d. Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole;

e. No particulate waste material falls into the borehole;

f. The exposure scenario includes only those radionuclides transported to the saturated zone by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the saturated zone); and

g. No releases are included which are caused by unlikely natural processes and events."

The specification of these assumptions informs which FEPs are included in the performance assessment as well as how the included FEPs are implemented. As required by proposed 10 CFR 63.321(a), the DOE must determine the earliest time after disposal that a waste package would degrade sufficiently that a human intrusion would occur without recognition by the drillers. Some FEPs, such as general corrosion of the drip shield and waste package, are considered in the determination of the time at which a human intrusion could occur as required by proposed 10 CFR 63.321(a), but are not included in the results of the performance assessment conducted to show compliance with proposed 10 CFR 63.321(b). As another example, the invert feature is not represented at all in the stylized analysis because the borehole allows radionuclides to bypass the invert (SNL 2008b, Section 6.7.1). The system-level human intrusion FEPs that are included in the human intrusion scenario are identified in Table 2.2-6.

2.2.1.4 Screening of Scenario Classes and Event Classes

[NUREG -1804, Section 2.2.1.2.1.3: AC 4; Section 2.2.1.3.1.3: AC 1(6); Section 2.2.1.3.2.3: AC 1(6); Section 2.2.1.3.3.3: AC 1(11), AC 3(5); Section 2.2.1.3.4.3: AC 1(7), AC 3(6); Section 2.2.1.3.7.3: AC 3(3); Section 2.2.1.3.9.3: AC 3(3)]

In Step 4 of the FEP analysis and scenario development process (Section 2.2.1), scenario class screening and event class screening are used to identify scenario classes or event classes that can be excluded from the performance assessments conducted to demonstrate compliance with proposed 10 CFR 63.311, proposed 10 CFR 63.321, and 10 CFR 63.331 based on probability, consequence, or consistency with the regulations.

The Nominal, Early Failure, Seismic, and Igneous Scenario Classes defined in Section 2.2.1.3 are based on initiating events with probabilities that are greater than one chance in 10,000 of occurring within 10,000 years of disposal, and, therefore, they are included in the performance assessment conducted to demonstrate compliance with proposed 10 CFR 63.311.

The Nominal, Early Failure, and Seismic Scenario Classes represent sequences of events and processes with exceedance frequencies greater than 10^{-5} per year and are therefore included in the performance assessment conducted to demonstrate compliance with 10 CFR 63.331. The Igneous Scenario Class represents sequences of events and processes with exceedance frequencies that are less than 10^{-5} per year, and it is therefore excluded from the performance assessment conducted to demonstrate compliance with 10 CFR 63.331 (SNL 2008b, Section 8.1.2).

The Human Intrusion Scenario Class, which is specifically developed to address the conditions defined at 10 CFR 63.322 for the Human Intrusion Scenario and demonstrate compliance with proposed 10 CFR 63.321, is not included in the performance assessments to demonstrate compliance with proposed 10 CFR 63.311 or 10 CFR 63.331. Proposed 10 CFR 63.311(a) and 10 CFR 63.331 are standards for releases from the undisturbed Yucca Mountain disposal system. 10 CFR 63.302 states "*Undisturbed Yucca Mountain Disposal System* means that the Yucca Mountain disposal system is not affected by human intrusion." The Human Intrusion Scenario Class is excluded from the performance assessments to demonstrate compliance with proposed 10 CFR 63.311 and 10 CFR 63.331 because it is specifically ruled out by regulation.

2.2.1.4.1 Screened-Out Event Class-Criticality

This section describes the nuclear criticality considerations for the repository during the postclosure period and reviews the technical basis by which nuclear criticality is screened from the postclosure performance assessment based on low probability. Per proposed 10 CFR 63.342(a), "DOE's performance assessments conducted to show compliance with 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal." In this section it is demonstrated that even with numerous and significant conservative but reasonable and defensible analysis assumptions (i.e., analysis assumptions that increase the calculated probability of criticality), the probability of nuclear criticality during the postclosure performance period is very unlikely. Therefore, the Criticality Event Class is screened-out on the basis of low probability.

Analyses of the in-package probability of criticality for naval spent nuclear fuel (SNF) are described in Section 2.2.1.4.1 of the Naval Nuclear Propulsion Program Technical Support Document. All following discussions and conclusions in this section regarding in-package probability of criticality apply only to commercial and DOE (except naval) SNF and high-level radioactive waste (HLW) glass. Subsequent discussions of near- and far-field criticality are applicable to naval SNF.

In consideration of the FEPs that can affect repository performance, a criticality event is unique in that it requires a combination of FEPs to occur before the event itself is possible. Individual criticality FEPs are screened-out from affecting repository performance as other FEPs are, but are also considered collectively in determining the screening justification for the Criticality Event Class. Consequently, the criticality event requires a more detailed screening discussion than might otherwise be warranted.

A nuclear criticality event is the occurrence of a self-sustaining nuclear chain reaction in fissionable material, such as those contained in waste forms identified for disposal in the repository. A criticality event involves a set of complex processes affecting the production and loss of neutrons where the overall net ratio of these effects is characterized by the effective neutron multiplication factor, k_{eff}, that is equal to or greater than 1.0 for a critical or supercritical system, respectively. A nuclear criticality event in the repository after closure could result in the generation of additional radionuclide inventory and energy in the form of heat and radiation, and hence could have an impact on the overall system performance. Consequently, multiple barriers (both natural and engineered) and administrative loading procedures (for commercial SNF) are integrated into the repository design and operations, and relied upon to limit the potential for criticality during the postclosure phase of the repository. Each waste form is analyzed for criticality potential to determine the potential impact, if any, of criticality on the overall system performance. These analyses include an evaluation of the effectiveness of measures, implemented before closure of the repository, that are designed to minimize the criticality potential of waste forms (i.e., waste package internals and neutron absorbers as identified in Table 1.9-8). These measures are relied upon to maintain their effectiveness over a minimum of 10,000 years as the waste package and waste form configurations change due to degradation, disruptive events, and environmental changes in the repository. The most significant and effective measures for prevention of criticality in the repository are the following (YMP 2003, Sections 1.1 and 1.2):

- The multiple, redundant barriers that act to isolate the fissionable material from water (which can act as a moderator, corrosive agent, and transporter of fissile material)
- The inherent geometry of the waste package internals and waste forms
- The presence of fixed neutron absorbers in the waste package internals
- Fuel burnup for commercial SNF.

It is important to note that the majority of the waste form types being loaded into the repository (i.e., commercial spent nuclear fuel) have been discharged from a nuclear power reactor because their material composition and amount of fissile material are no longer effective in supporting criticality for power generation. In the absence of any of the low probability initiating events for the four scenario classes considered, the waste packages and drip shields are expected to retain their functionality and isolate the fissionable material from moderator (i.e., water). Hence, the waste forms remain dry (i.e., unmoderated) and are subcritical by a very large margin (i.e., a criticality event is not credible). To ensure a criticality event does not occur in the repository, the disposal canisters were designed such that the initial emplaced configuration of all of the waste forms remain subcritical, even under flooded conditions (SNL 2008d, Section 6.2.2; Radulescu, Moscalu et al. 2004, Sections 10 and 11.4; BSC 2004a, Section 6; BSC 2004b, Section 6). Therefore, for criticality to occur inside the waste package, all of the following must occur (SNL 2008e, Section 6.2): (1) immediate or delayed waste package damage (barriers breached); (2) presence of a moderator (i.e., water); and (3) the materials inside the package must degrade and/or reconfigure (e.g., separation of fissionable material from the neutron absorber material or lack of absorber material). For criticality to occur outside the waste package, there must be a sufficient accumulation of a critical mass of fissionable material. The probability of a criticality is insignificant unless all necessary conditions occur, and then is only representative of an upper bound because the probability distributions associated with many of the events required to induce criticality have been conservatively set to 1.0 in order to maximize the quantified probability of criticality potential (SNL 2008e, Section 6.2). The discussions that follow provide the basis for the conclusion that the probability of a nuclear criticality event in the repository is below the regulatory threshold for inclusion in the postclosure performance assessments (i.e., less than one chance in 10,000 of occurring within 10,000 years after disposal).

Table 2.2-2 includes a listing of the 16 FEPs associated with nuclear criticality. The criticality FEPs are divided into three locations for four initiating event scenarios. The three locations are: internal to the waste package in an intact or degraded condition, near field, and far field. The four initiating event scenarios are nominal, seismic, rockfall, and igneous. These scenarios are different from the scenario classes described in Section 2.2.1.3. The scenario classes described in Section 2.2.1.3 were formulated for the purposes of analyses of included events in the performance assessments. The Criticality Event Class requires waste package failure in the event sequence, therefore, an initiating event must occur that causes a breach of the waste package before any other sequence of events on that waste package could lead to criticality. In the Nominal Scenario Class defined in Section 2.2.1.3, there are no waste package failures within 10,000 years following disposal. The early waste package failures in the Early Failure Scenario Class described in Section 2.2.1.3 are considered in the nominal scenario for the Criticality Event Class. An Early Failure is defined as the through-wall penetration of a waste package or drip shield due to manufacturing or handling-induced defects, at a time earlier than would be predicted by mechanistic degradation models for a defect-free waste package or drip shield. Additionally, the seismic scenario for the Criticality Event Class differs from the Seismic Scenario Class defined in Section 2.2.1.3 in that rockfall damage from seismic events is considered separately from other damage resulting from seismic events.

2.2.1.4.1.1 Criticality Analysis Methodology

A risk-informed, performance-based methodology for analysis of postclosure nuclear criticality events is presented in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003). The topical report contains a description of generalized degradation scenarios summarized in a master scenario list and the overall methodology for evaluating the potential for and the possible consequences of a nuclear criticality event. The methodology establishes the means for identifying potential configurations, determining a configuration's criticality potential, establishing the probability of criticality, and analyzing the consequences of a criticality event, if applicable. The topical report also describes the process for validating the criticality-specific models to implement the methodology.

The analyses performed to evaluate criticality potential (SNL 2008e) in the postclosure environment were conducted using the methodology described in the topical report (YMP 2003), which is in accordance with the guidance in the Yucca Mountain Review Plan and demonstrates compliance with proposed 10 CFR 63.114(a)(6) and (a)(7).

2.2.1.4.1.1.1 Process

The evaluation of the potential for nuclear criticality in the repository using the disposal criticality analysis methodology begins with the identification of applicable configuration classes for the waste forms and waste packages being disposed. A configuration class is an end state of a general degradation scenario process associated with the master scenario list that establishes such scenarios (YMP 2003, Section 3.3). Potential critical configurations are states defined by a set of parameters characterized by the quantity and physical arrangement of materials that have the potential to cause nuclear criticality. The parameters are determined from design characteristics of the waste package and other EBS systems, structures, and components; waste form characteristics; and repository site characteristics. There are various uncertainties associated with these parameters that depend on the combination of FEPs that result in the degraded configurations. These uncertainties are accounted for in the criticality evaluation to establish a probability of criticality associated with a particular configuration class.

The general degradation processes, scenarios, and locations are expanded and refined in a configuration generator model (BSC 2004c) based on the event tree/fault tree methodology of risk assessment (described below) to define the specific configuration classes that are to be evaluated. The resulting configuration parameters are associated with degradation sequences that have been identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Section 3.3). A subset of the configuration parameters is obtained from geochemical analyses of scenarios both internal and external to a waste package. The configuration classes are sorted and grouped by their associated locations and scenario classes. The locations and scenarios define the 16 FEPs associated with criticality. These FEPs address scenarios that include initiators of sequences of events or processes that could lead to configurations that have potential for criticality in the repository. The evaluation of these FEPs is developed and documented in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e), which considers the occurrence of configurations with potential for criticality in the entire repository based on contributions from all initiating events. The justification for the screening decision is summarized in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008a).

An overview of the disposal criticality analysis methodology is provided in Figure 2.2-4. This figure illustrates the process flow through the disposal criticality analysis methodology and shows the input streams required, decision points in the methodology, and test criteria. The major steps in the analysis methodology are summarized below.

Potential criticality scenarios are evaluated in a systematic manner using either cogent but nonquantitative arguments (SNL 2008e, Section 1.4) or an event tree methodology as documented in the *Configuration Generator Model* (BSC 2004c). The latter process is quantitative where the characteristics of the waste form, waste package, drip shield and repository (Items 2, 3, and 4 of Figure 2.2-4), as well as the geochemical performance characteristics (Item 5), are used to develop and define end states that represent the configuration classes derived from criticality scenarios (Items 6 and 7). The methodology focuses on evaluation of the probability of occurrence of configurations with potential for criticality and the probability of criticality for those configurations.

Once the applicable configuration classes are identified and grouped according to their corresponding criticality FEPs, initial probability estimates can be made for each class. Any configuration class whose probability of occurrence is below the a priori probability screening criterion (Item 1 of Figure 2.2-4) is not evaluated further. A configuration class is considered to have potential for criticality if the probability of the configuration class formation is above the a priori probability screening criterion. Having potential for criticality does not mean that a configuration is or even can be critical but that the configuration must be further analyzed for criticality possibilities. This criterion is used to screen from further consideration configuration classes that contribute insignificantly to the total probability of a criticality occurring within the 10,000 years after disposal where insignificant means an evaluation that the probability of the event, if known, would not change the overall result.

The criterion for screening the initial configuration class probability (Item 1 of Figure 2.2-4) is set to a minimum of 2 orders of magnitude below the proposed 10 CFR 63.342(a) probability criterion for exclusion of events from performance assessments conducted to show compliance with proposed 10 CFR 63.311, proposed 63.321, and 63.331 (i.e., one chance in 10,000 of occurring within 10,000 years of disposal). This criterion will ensure that no single configuration class is excluded that could contribute significantly to the total probability of criticality.

The second decision point in the disposal criticality analysis methodology is a test on the criticality acceptance criterion (Item 2 of Figure 2.2-4) that is based upon the critical limit for the scenario class, configuration class, and waste form. The critical limit is the value of k_{eff} at which the configuration class is considered potentially critical as characterized by statistical tolerance limits obtained by analysis of experimental systems with a range of physical and neutronic parameters that are representative of the configuration class parameters expected in the repository (BSC 2004d, Section 6.1).

Configuration classes that satisfy the criticality acceptance criterion are those that remain subcritical for 10,000 years after repository closure, and their probability of criticality is set to zero (insignificant contribution to the total probability of criticality) (SNL 2008e, Section 1.4). Configuration classes that do not satisfy the criticality acceptance criterion for the waste form are further analyzed to estimate their probability of criticality (Item 3 of Figure 2.2-4). The probability of criticality is estimated for each configuration class as a function of the characteristics of the waste form. This overall process is applied to all waste package types applicable to a waste form (Item 4 of Figure 2.2-4) and to all waste forms (Item 5 of Figure 2.2-4) (YMP 2003). The probability associated with a particular sequence of events is a monotonically decreasing function as additional events are included in the sequence. Hence, the estimated probability of criticality is a bounding value because the probabilities of events not explicitly evaluated cannot exceed 1.0.

A design probability criterion for the probability of a single criticality occurring to be less than one over the entire repository for the first 10,000 years is imposed as a criticality control limit. The total probability of criticality is compared to the design probability criterion (Item 6 of Figure 2.2-4), and, if equal to or greater than the design probability criterion, then criticality mitigating strategies are required that may include a redesign of the waste package, criticality controls, or other components as necessary to reduce the total probability of criticality and meet the design probability criterion. The design probability criterion has been met; therefore, the Item 6 decision point results in a "yes." The total probability of criticality is next checked against the criterion for event inclusion in the performance assessments (Item 7 of Figure 2.2-4). If the total probability of criticality is below the criterion for event inclusion in the performance assessments, the repository design is acceptable with respect to criticality (Item 11 of Figure 2.2-4), and criticality can be excluded from the performance assessments. As shown in Table 2.2-8, the Item 7 decision point results in a "yes" outcome. Therefore, the methodology terminates with Item 11 indicating an acceptable design. The alternate path, in which the total probability of criticality is equal to or greater than the criterion for event inclusion in the performance assessments and thus cannot be excluded, is described in Items 8, 9, and 10 of Figure 2.2-4. These items identify the additional analyses required (e.g., performing criticality consequence analyses and conducting performance assessments to demonstrate compliance with regulatory performance objectives) if a criticality event cannot be excluded.

2.2.1.4.1.1.2 Calculations

Nuclear criticality calculations are performed to determine the critical limit for each scenario class, configuration class, and waste form and to evaluate the calculated k_{eff} value for relevant configurations against the critical limit. Criticality calculations are also used to evaluate key parameters (e.g., fuel enrichment, fuel configuration, and absorber composition) important to criticality. These calculations, which are performed with well-established computer codes and nuclear data, are summarized in the following sections. Details of the calculations are provided in the referenced analysis reports.

Note that an essential element in the criticality event screening evaluation for the most prevalent waste form, commercial SNF, is the calculation of the reduced reactivity associated with fuel burnup. These calculations utilize an established depletion code for determination of conservative fuel contents (i.e., fuel compositions that result in an over-estimation in the calculated k_{eff} value), as described below in Section 2.2.1.4.1.1.2.2, and account for the additional considerations associated with such analyses (e.g., fuel operating conditions, spatial burnup distributions, and exclusion of gaseous and volatile nuclides).

2.2.1.4.1.1.2.1 Design Basis Configurations

Consistent with standard practice in criticality safety evaluations for licensing, design basis configurations are developed and used in the postclosure criticality evaluation to bound, in terms of reactivity, possible relevant variations for each waste form. Waste form loading criteria (e.g., loading curves for commercial SNF) are developed based on analyses with the design basis configuration. Criticality analyses for configurations that have the potential for criticality (e.g., from an initiating event) are performed to demonstrate that the reactivity of such configurations is bounded by the reference design basis configuration. If, during the process of these analyses, a configuration was identified that was more reactive than the design basis, the design basis configuration would be revised to ensure it is bounding.

Irrespective of the relevant probabilities, for all waste forms the design basis configuration that is used to assess the potential for a criticality event assumes full flooding with water and neutron absorber material that is degraded, beyond the maximum credible extent (SNL 2008d, Table 7-3). For commercial SNF types, the design basis configuration includes full flooding with unborated water, reduced thickness of neutron absorber to account for 10,000 years of corrosion, the most reactive pressurized water reactor (PWR) and boiling water reactor (BWR) fuel types, and a close-packed arrangement of the fuel assemblies and fuel basket tubes in the waste package (i.e., no credit for flux traps or other means for geometric separation that may be designed into transportation, aging, and disposal (TAD) canisters). Additional specific modeling representations used for the design basis configuration calculations are listed in Section 2.2.1.4.1.1.2.2.

2.2.1.4.1.1.2.2 Analysis Considerations

Consistent with applicable industry standards and regulatory guidance, the criticality analysis considers relevant variations in the configurations, waste packages, waste forms, and input assumptions to ensure a conservative (with respect to criticality) representation of the evaluated systems. To ensure that the calculated k_{eff} value is always greater than the actual k_{eff} value, the following modeling considerations and conservative assumptions are used to define the design basis configurations in performing the criticality calculations for each configuration:

- The waste packages are assumed to contain the most reactive fuel form (e.g., assembly design) for the configuration. In the case of commercial SNF, all assemblies are assumed to be the most reactive fuel assembly design (Babcock and Wilcox (B&W) 15 × 15 (SNL 2008d, Section 6.1.1.2.1) and General Electric (GE) 7 × 7 (SNL 2008d, Section 6.1.1.2.1) for PWR and BWR, respectively), as determined by comparisons of the relevant assembly designs in configurations relevant to postclosure criticality. In the case of DOE SNF, representative waste forms are used for fuel groupings (Section 1.5.1.3.1.1.3). The term representative means that all fuels would perform similarly regarding chemical interactions within the waste package and basket, and that canister loading limits from the representative fuel (ranges of key parameters important to criticality such as linear fissile loading and total fissile mass) are established such that they will not be exceeded by other fuels within the group. The representative waste forms for the criticality DOE SNF fuel groups are listed in Section 1.5.1.3.1.1.

- For DOE SNF, a comprehensive evaluation of various states of degradation from fully intact to fully degraded configurations is performed, and criticality control limits are set based on maintaining subcriticality for the most restrictive degraded scenario, for each criticality DOE SNF fuel group (Radulescu, Moscalu et al. 2004; BSC 2004a; BSC 2004b).

- Conservative modeling representations (i.e., modeling representations that increase the calculated k_{eff} value) are used for all waste form and waste package geometric and material representations, including material and fabrication tolerances and uncertainties (Radulescu, Moscalu et al. 2004, Section 10; BSC 2004a, Section 6; BSC 2004b, Section 6; SNL 2008d, Section 6.1).

- Commercial SNF stack density is assumed to be 98% of theoretical (10.74 g/cm^3).

- Neutron absorber thickness used in the TAD canister is less than the predicted thickness based on general corrosion for 10,000 years (6 mm used; ≥9 mm predicted (SNL 2008d, Section 6.2.4.3).

- The waste packages are assumed to be moderated to the most reactive credible extent. For any potential moderator present, such as water, appropriate ranges of quantity and density are evaluated to ensure that the range of values includes the most reactive, credible condition (SNL 2008d, Section 6.2.2). For commercial SNF, the loading curves are based on moderation with full density water (SNL 2008d, Table 7-3).

- Consistent with guidance in NUREG-1536 (NRC 1997, Section 6 (IV)(4)(c)), for fixed-neutron absorbers used for criticality control in the packages, no more than 75% credit for the neutron absorber content is modeled (i.e., the design-specified absorber content is reduced by 25% in the analyses) (SNL 2008d, Table 7-3).

- The waste packages are modeled to be reflected to the most reactive credible extent (SNL 2008d, Section 6.2.2 and Table 7-3).

- Except for commercial SNF all DOE SNF fuel forms are assumed to be fresh or at their most reactive credible condition (i.e., no credit for fuel burnup, calculated most reactive state for breeder DOE SNF) (Radulescu, Moscalu et al. 2004, Section 3.1.2.4).

- For burnup credit in commercial SNF, conservative modeling representations with respect to criticality are used throughout with respect to the commercial SNF material concentrations, including the following:

  – Use of isotopic compositions corresponding to the time period of maximum fuel reactivity (i.e., 5-year decay), which is not actually possible given the preclosure time frame (100 years (Section 1)) and the current requirement (10 CFR 961.11, Appendix E (B)(3)) for commercial SNF to have at least 5-year cooling to be considered standard fuel. Note that emplacement operations are expected to be completed within the first 50 years with an additional 50 years to satisfy closure requirements (Section 1). Therefore, any waste that is emplaced will have cooled more than 5 years. This modeling representation is used in conjunction with the use of a minimum neutron absorber thickness, which corresponds to the maximum duration of corrosion (i.e., 10,000 years).

  – No credit is taken for the significant thermal neutron absorption by ^{133}Cs (Parrington et al. 1996, p. 34) or any of the gaseous fission products.

- Conservative values (BSC 2003a, Section 5.1; Wimmer 2004, Section 5.1) are simultaneously applied to all of the relevant depletion parameters, leading to maximum reactivity for the spent fuel compositions, including the following:
  - Fuel temperature: 1,600 °F (871.1 °C) for PWR and 1,700.3 °F (926.8 °C) for BWR.
  - Moderator temperature: 600 °F (315.6 °C) for PWR and 549.9 °F (287.7 °C) for BWR.
  - Moderator density: 0.6905 g/cm^3 for PWR and 0.30 g/cm^3 for BWR.
  - Boron concentration: 1000 ppm boron, constant (no boron letdown curve) for PWR.
  - Specific power: 30 MW/MTU for PWR and 22.38 MW/MTU for BWR.
  - High absorber content (3.5 wt % B_4C) solid burnable poison rods are left inserted in all guide tube locations for all depletion cycles (PWR).
  - Control blades inserted for final 15 GWd/MTU, no gadolinium rods for BWR. Since the maximum burnup required for BWR fuel is less than 15 GWd/MTU (SNL 2008d, Table 6-28), this assumption corresponds to the control blades being inserted during the entire depletion. This modeling representation results in significant conservatism (with respect to criticality) in the calculated isotopic compositions (Anderson 2003, Section 6.5; Wimmer 2004, Section 5.1.1.5).
- A conservative representation (i.e., a representation that increases the calculated k_{eff} value) of axial burnup is used in the development of the PWR loading curves— either uniform axial burnup or conservative burnup-dependent axial profiles, depending on which representation yields the highest k_{eff} value (SNL 2008d, Section 6.3.2). For low burnup values, the uniform axial burnup representation yields a higher k_{eff} value than an explicit representation (BSC 2003b, Section 6).
- Loading curves are developed based on all assemblies characterized by the conservative modeling representations (i.e., modeling representations that increase the calculated k_{eff} value) described above and having burnup and enrichment combinations that correspond exactly to the loading curve (SNL 2008d, Sections 6.3 and 7). In reality, loaded assemblies will not be as reactive as the analyses predict due to the conservative modeling representation used and the fact that loaded assemblies will have higher than the minimum required burnup for loading.
- For external, near- and far-field criticality analyses, conservative modeling representations include the following:
  - The fissile material accumulates in a single location and in the most reactive possible geometry (SNL 2007a, Section 6.9.2[a]).
  - No credit assumed for fuel burnup or the presence of absorbing materials within the mass of the accumulated fissile material (SNL 2007a, Section 6.9.1[a]).

– Moderation and reflection are evaluated and are assumed at their most reactive credible extents (SNL 2007a, Sections 6.9.1[a] and 6.9.2[a]).

– Geochemistry analyses represent degradation and external accumulation processes and characteristics to maximize the mass of material that accumulates outside of the package (SNL 2007b, Section 8.1; SNL 2007a, Section 8.1).

The individual modeling assumptions listed above each contribute to an over-estimation of the calculated k_{eff} value, in some cases a large over-estimation (e.g., >1% Δk) (BSC 2001, Sections 5.3 and 6; BSC 2004e, Section 8). Collectively, these assumptions result in a substantial over-estimation of the calculated k_{eff} value (e.g., >5% Δk, as compared to typical discharged commercial SNF) (BSC 2003a, Table 23), and hence provide substantial margin in the analysis predictions and loading curves.

Additional considerations include the following (SNL 2008d, Sections 6.3 and 6.4):

- Reductions in the critical limit to account for isotopic (for commercial SNF) and criticality bias and bias uncertainty
- Misloading of waste forms into a waste package or other container
- Misloading of neutron absorber panels during fabrication
- Increase in the minimum required assembly burnup (by 5%) in the loading curves to account for uncertainties in commercial SNF assembly burnup values.

2.2.1.4.1.1.2.3 Analysis Software

Criticality evaluations are performed using the standard, well-established computer codes discussed below, which include MCNP and SCALE for criticality analyses and SCALE/SAS2H for depletion calculations. Geochemical analyses are performed with the EQ3/6 and PRHEEQC software packages.

2.2.1.4.1.1.2.3.1 MCNP Version 4B2LV

The MCNP code, version 4B2LV and accompanying nuclear data, based primarily on ENDF/B-V, are used to calculate the k_{eff} for the various DOE SNF waste form compositions. MCNP is designed to perform Monte Carlo solutions to particle transport, including k_{eff} calculations for fissile materials (Briesmeister 1997, Chapter 2, Section VIII). Relevant code recommendations (e.g., use of the combined collision, absorption, and track-length estimator) and appropriate user parameters (e.g., number of histories per cycle, number of skip cycles, and number of total cycles) are used to ensure convergence of the k_{eff} predictions. MCNP, version 4B2LV, is validated for use in *Criticality Model* (BSC 2004d).

2.2.1.4.1.1.2.3.2 MCNP5 Version 1.40

The MCNP5 code, version 1.40, and accompanying nuclear data, based primarily on ENDF/B-VI, are used to calculate the k_{eff} for the various commercial SNF configurations. MCNP is designed to perform Monte Carlo solutions to particle transport, including k_{eff} calculations for fissile materials (LANL 2004, Chapter 2, Section VIII). Relevant code recommendations (e.g., use of the combined collision, absorption, and track-length estimator) and appropriate user parameters (e.g., number of histories per cycle, number of skip cycles, and number of total cycles) are used to ensure convergence of the k_{eff} predictions. MCNP is validated for use in *Range of Applicability and Bias Determination for Postclosure Criticality of Commercial Spent Nuclear Fuel* (Radulescu, Mueller et al. 2007).

2.2.1.4.1.1.2.3.3 SCALE Version 4.4A

The SAS2H control module of the SCALE code system, version 4.4A, and accompanying nuclear data, based primarily on ENDF/B-V, are used to perform the fuel assembly isotopic depletion calculations required for PWR and BWR commercial SNF to develop criticality loading curves for criticality safety. Relevant code recommendations (e.g., for assembly modeling) and appropriate user parameters (e.g., use of the sufficiently refined burnup time steps) are used to improve accuracy and reliability of the isotopic composition predictions. Isotopic depletion calculations for the waste forms are required to determine the isotope inventory so that subsequent criticality safety calculations may be performed. SAS2H is validated for use in *Isotopic Model for Commercial SNF Burnup Credit* (BSC 2004e).

2.2.1.4.1.1.2.3.4 SCALE Version 5.1

Several modules of the SCALE code system, version 5.1, and accompanying nuclear data, based primarily on ENDF/B-VI, were used to perform criticality calculations. The XSDRNPM module was used to evaluate the criticality of uranium and plutonium minerals that may accumulate in the invert below the waste package or in the host rock below the invert (SNL 2007a) (i.e., near- and far-field criticality). XSDRNPM is a discrete-ordinates code that solves the one dimensional Boltzmann transport equation in slab, cylindrical, or spherical geometries. All XSDRNPM calculations used the 238-group ENDF/B-VI cross section library provided as a standard component of the SCALE code system. The cross sections were self-shielded and resonance-processed with the BONAMI, CENTRM, and PMC modules to treat the small-scale heterogeneity effects. The CSAS25 control module, which includes the KENO V.a three-dimensional Monte Carlo criticality code, was used for independent confirmatory calculations for the range of applicability and bias determination studies related to the validation of MCNP for commercial SNF (Radulescu, Mueller et al. 2007). Finally, the SCALE sensitivity/uncertainty tools (TSUNAMI) were used in the determination of applicable critical experiments for validation of MCNP for commercial SNF.

2.2.1.4.1.1.2.3.5 EQ3/6

EQ3/6 is a software package for geochemical modeling of aqueous systems, which includes: EQ3NR, a speciation-solubility code, and EQ6, a reaction path code which models water and solid interaction (Wolery 1992). EQ3/6, improved and expanded since its development in the 1970s, has been validated by comparison with experimental data (SNL 2003). The software is used along with a supporting thermodynamic database (SNL 2007c), which was developed for Yucca Mountain Project-related geochemical modeling. For criticality applications, EQ3/6 V.8.1 is used to simulate the degradation of waste package components once aqueous solutions have entered the waste package and to determine the retention or mobilization of the radionuclides and the neutron-absorbing material during the 10,000 years after repository closure (SNL 2007b).

2.2.1.4.1.1.2.3.6 PHREEQC

PHREEQC, developed by the U.S. Geological Survey, is a computer program for simulating chemical reactions and transport processes in aqueous environments (Parkhurst and Appelo 1999). PHREEQC has been validated with comparisons to other EQ3/6 results and with comparisons to analytical solutions and hand calculations (CRWMS M&O 2001). For criticality applications, the external accumulation model uses PHREEQC V.2.3 to simulate the transport and interaction of the waste package effluent with the resident water and crushed tuff in the invert or in the host rock (SNL 2007a). In the PHREEQC simulations, the primary mechanisms for accumulation are adsorption and precipitation. Adsorption of the actinides occurs on the tuff surfaces within the invert or the fractured rock. The precipitation occurs as a result of mixing the actinide-laden waste package effluent with resident water, thus changing the chemistry sufficiently for fissile minerals to become insoluble and precipitate. The PHREEQC code is used in conjunction with the same thermodynamic database used for EQ3/6, but converted to a format suitable for PHREEQC.

2.2.1.4.1.1.2.4 Isotopic and Criticality Validation Methodology

Validation is the process of determining the applicability of a computational method and establishing the bias of the method by comparison of computational results for experimental benchmarks appropriate for the intended evaluation of operations. The validation process is performed for the fuel depletion computational method (isotopic model) and for the neutron multiplication factor computational method (criticality model). The validation methodology for the criticality and isotopic models is described in the following sections and is performed in accordance with ANSI/ANS 8.1-1983, Section 4.3 and Appendix C. Regulatory Guide 3.71 endorses the use of ANSI/ANS-8 nuclear criticality safety standard documents and states that the procedures and recommendations in the ANSI/ANS-8 standards should be followed to prevent and mitigate nuclear criticality event sequences.

2.2.1.4.1.1.2.4.1 Isotopic Model Validation

For commercial SNF, the isotopic calculation methodology uses the SAS2H control module of the SCALE code system to apply the transition matrix method along with a nuclear data library to solve the transmutation and radioactive decay equations that describe the isotopic changes as fuel is irradiated in a reactor. Isotopic concentrations are calculated for the principal isotopes listed in Table 2.2-9, which includes 14 actinide and 15 fission product nuclides. Subsequently, these isotopic compositions are utilized in the criticality models for commercial SNF. A bias, in terms of Δk, is determined for the set of principal isotopes, based on comparisons between calculated and measured data, and is used to reduce the critical limit value to account for bias and bias uncertainty in the isotopic predictions. The actual value that is applied for both PWR and BWR SNF is 0.0249 Δk (BSC 2004e, Section 6.2.2), for all values of burnup.

Although SAS2H uses a one-dimensional transport calculation, it is one of the most widely used and verified programs for such calculations. The adequacy of SAS2H has been demonstrated via comparisons of SAS2H results to experimental data, as well as computational results from a two-dimensional depletion program (BSC 2004e). Furthermore, any deficiencies associated with its use will manifest themselves in terms of the code bias and bias uncertainty that are accounted for in the determination of the critical limit.

The validation of the isotopic model (SAS2H) calculations considers commercial reactor critical and radiochemical assay data from both PWRs and BWRs to determine the bias and bias uncertainty in calculated k_{eff} values associated with the computed isotopic compositions. The bias and bias uncertainty of the commercial reactor critical and radiochemical assay data k_{eff} values are evaluated in *Isotopic Model for Commercial SNF Burnup Credit* (BSC 2004e). The overall reactivity bias for the commercial reactor critical data is quantified by calculating k_{eff} between the measured (always 1.0) and calculated k_{eff} for each of 57 (41 PWR, 16 BWR) commercial reactor critical cases. For the radiochemical assay data, the bias and uncertainty in k_{eff} values is established by comparing reactivity calculations performed using measured isotopic concentrations from 104 (74 PWR, 30 BWR) assay samples with calculations performed using calculated isotopic concentrations for the assay samples obtained from the depletion code. The standard deviation of the data points is calculated as the pooled standard deviation of the k_{eff} calculations and the standard deviation of the average k_{eff}. The bias and bias uncertainty values based on the commercial reactor critical data and the measured radiochemical assay data are predicted to be −0.0077 and −0.0249 Δk, respectively (BSC 2004e, Tables 6 and 10, respectively). A confidence level of 95% is used in calculating the lower bound for the tolerance limit that covers 95% of the population for each data set. Note that the large bias and bias uncertainty for the radiochemical assay data is primarily a result of the uncertainty associated with the RCA data, which manifests itself as a higher penalty in the tolerance limit. To ensure conservatism (with respect to criticality) in the criticality evaluation, the larger of the CRC and RCA bias and bias uncertainty terms (i.e., 0.0249 Δk) is used as Δk_{ISO} in the determination of the critical limit. The term Δk_{ISO} and its application are described in Section 2.2.1.4.1.1.2.4.2.

Although independent of the isotopic validation, it is important to note that the reactor operating conditions and parameters used in the depletion calculations to calculate the isotopic compositions used in the criticality model are purposefully selected to ensure that the calculated reactivity of commercial SNF is conservative, i.e., reactivity is maximized. The selection and basis for these bounding parameters, which are listed in Section 2.2.1.4.1.1.2.2, are provided in *Isotopic Generation and Confirmation of the PWR Application Model* (BSC 2003a, pp. 15 to 20) and *Isotopic Generation and Confirmation of the BWR Application Model* (Wimmer 2004 pp. 16 to 18) for PWR and BWR commercial SNF, respectively. Calculated isotopic compositions for PWR and BWR commercial SNF at selected initial enrichment and burnup combinations are provided in Table 2.2-10. The *Isotopic Model for Commercial SNF Burnup Credit* (BSC 2004e) provides an evaluation of the sensitivity of k_{eff} to variations in the relevant depletion conditions and parameters used to calculate the SNF isotopic compositions. Additionally, this report provides estimates of the impact on k_{eff} associated with the use of the selected conservative parameters, as compared to the use of more typical or nominal conditions and parameters. The combined use of the bounding conditions and parameters in the depletion calculations and the application of the Δk_{ISO} term in the determination of the critical limit provides assurance that the isotopic compositions for the commercial SNF are handled in a conservative manner.

2.2.1.4.1.1.2.4.2 Criticality Model Validation

The criticality model validation process is provided in *Criticality Model* (BSC 2004d) and in *Range of Applicability and Bias Determination for Postclosure Criticality of Commercial Spent Nuclear Fuel* (Radulescu, Mueller et al. 2007). The criticality model validation process is shown in Figure 2.2-5. Waste form configurations resulting from normal operations and event sequences involving criticality are subdivided into classes of similar physical and material characteristics (e.g., fissile isotopes, enrichment, moderator-to-fissile material ratio). For each configuration class, a range of parameters is established. The validation process is then performed.

An essential element for validating the criticality computational method used for calculating k_{eff} for a waste form configuration is the determination of the critical limit (CL). The CL includes the bias and bias uncertainty associated with the criticality code and nuclear cross section data. The CL for a configuration class is a limiting value of k_{eff} at which a configuration is considered potentially critical. The CL is characterized by statistical tolerance limits that account for biases and uncertainties associated with the criticality code (i.e., the determination of the lower bound tolerance limit), and any uncertainties due to extrapolation outside the range of experimental data, as well as limitations in the geometrical or material representations used in the computational method. The process for calculating the lower bound tolerance limits is shown in Figure 2.2-6. In the case of commercial SNF, where fuel burnup is considered, the CL also includes a penalty for isotopic composition bias and bias uncertainty, as described in Section 2.2.1.4.1.1.2.4.1.

The CL is represented as:

$$CL(x) = f(x) - \Delta k_{EROA} - \Delta k_{ISO} - \Delta k_m \quad \text{(Eq. 2.2-1)}$$

where

x = a neutronic parameter used for trending

$f(x)$ = the lower bound tolerance limit function accounting for biases and uncertainties that cause the calculation results to deviate from the true value of k_{eff} for a critical experiment, as reflected over an appropriate set of critical experiments

Δk_{EROA} = penalty for extending the range of applicability

Δk_{ISO} = penalty for isotopic composition bias and bias uncertainty (0.0249 Δk for commercial SNF)

Δk_m = an arbitrary margin ensuring subcriticality and turning the CL function into an upper subcritical limit function. This term is not applicable for use in postclosure analyses because there is no risk associated with a subcritical event. In contrast to “traditional” nuclear criticality safety analyses and associated governing regulations, in which the purpose is to ensure

> prevention of criticality and corresponding protection of personnel and facilities, the purpose of the postclosure criticality evaluation is to determine the probability of a criticality event in the postclosure time period. The probability of criticality is then compared to the regulatory screening criterion (one chance in 10,000 of occurring within the 10,000 years after disposal) to reach a decision relative to the inclusion or exclusion of a criticality event in the evaluation of the total system performance. In this sense, a criticality event is evaluated in the same manner as other events that have potential to impact the total system performance.

A CL is associated with a specific type of waste package and its state (intact or various stages of degradation described by the master scenarios (YMP 2003, Figures 3-2a and 3-2b). The lower bound tolerance limit function (criticality code bias and bias uncertainty) is established based on an evaluation of a representative set of benchmark critical experiments. This set of critical experiments also prescribes the basic range of applicability of the results. In the case of commercial SNF, the set of critical experiments includes publicly available mixed-oxide (PuO_2 and UO_2) and low-enriched uranium critical experiments from the International Handbook of Evaluated Criticality Safety Benchmark Experiments (NEA 2006b), proprietary HTC mixed-oxide critical experiments, and commercial reactor criticals. HTC refers to "Haut Taux de Combustion," which is a French designation for "high burnup." The 156 HTC critical experiments were performed in France with fuel pins having uranium and plutonium isotopic compositions that were designed to be similar to PWR fuel that had an initial enrichment of 4.5 wt % ^{235}U and was burned to 37,500 megawatt days per metric ton of uranium (MWd/MTU). For the commercial reactor criticals, an uncertainty of 2% (2 standard deviations) in k_{eff} is used to account for uncertainties in the commercial reactor critical configurations (Radulescu, Mueller et al. 2007).

The validation process used for the criticality model can be summarized in four steps: (1) selection of benchmark experiments; (2) establishment of the range of applicability of the benchmark experiments; (3) extension of the range of applicability (as necessary); and (4) development of critical limits. The critical limits as calculated from Equation 2.2-1 that are used in the evaluation of postclosure criticality are summarized in Table 2.2-11.

2.2.1.4.1.1.2.5 Criticality Loading Curves

Criticality loading curves are generated to determine combinations of enrichment and burnup that would preclude criticality in packages that are flooded and degraded (i.e., closely packed geometry and reduced neutron absorber thickness). The criticality loading curves are used in probabilistic evaluations for the postclosure period to evaluate the probability of criticality as a result of a misload (i.e., not loading according to the loading curves). The loading curves are generated using the design basis configurations described in Section 2.2.1.4.1.1.2.1.

2.2.1.4.1.1.3 Use of Criticality Loading Curves for Transportation, Aging, and Disposal Canisters

The TAD canisters will be loaded with commercial SNF at the respective power facilities according to loading curves and shipped to the repository for aging (if needed) and subsequent disposal. Loading curves, which are functions of burnup and enrichment, are the loci of values delineating the region of acceptable burnup/enrichment combinations for postclosure criticality control. In applying this methodology, the loading curve is generated once and the assigned burnup values of all assemblies considered for loading into the TAD canister are compared directly against this loading curve. Assemblies having burnup values in the unacceptable range (i.e., below the minimum required burnup) must be loaded into canisters with additional reactivity control mechanisms (e.g., disposal control rod assemblies) (DOE 2008, Section 3.1.5(2)(a)(6)). Canisters loaded in this manner must be individually analyzed to show acceptable reactivity control for postclosure performance prior to receipt and acceptance at the repository. The process for developing the criticality loading curves for each canister configuration and range of commercial SNF characteristics is documented in *CSNF Loading Curve Sensitivity Analysis* (SNL 2008d) and described below.

2.2.1.4.1.1.4 Development of Criticality Loading Curves

The process for developing the criticality loading curves for each canister configuration and range of commercial SNF types involves the following steps (SNL 2008d):

1. Commercial SNF isotopic concentration data are generated for a range of enrichment and burnup pairs using the process described in the isotopic model report (BSC 2004e).

2. TAD configurations to be evaluated for postclosure are determined (i.e., design basis configurations).

3. The CL for the postclosure configurations is determined, as described previously in Section 2.2.1.4.1.1.2.4.2.

4. A curve of calculated k_{eff} plus 2σ versus burnup is generated for the design basis configuration selected from Step 2 for a range of initial enrichments. The intersection of the calculated k_{eff}-versus-burnup curve and the CL defines the required minimum burnup for the selected initial enrichment value.

5. The required minimum burnup values from Step 4 for different initial enrichments are adjusted to account for uncertainty in the reactor record assigned burnup values. Specifically, the minimum required burnup is increased by 5% to accommodate uncertainties in the reactor record assigned burnup values.

6. An equation is fit to the adjusted burnup values from Step 5 and plotted as a function of initial enrichment to generate the criticality loading curve. The area above the curve includes the acceptable SNF burnup-enrichment combinations because the burnup in this area exceeds the required minimum burnup. The area below the curve defines unacceptable SNF that cannot be loaded into the particular waste package. Figures 2.2-7 and 2.2-8 illustrate criticality loading curves used for criticality control.

2.2.1.4.1.1.4.1 Source of Commercial SNF Burnup Values

Waste packages are loaded with commercial SNF assemblies that satisfy the minimum burnup requirements specified by the criticality loading curves (SNL 2008d). The burnup value assigned by the originating nuclear utility to each SNF assembly (assigned burnup) (e.g., the value used for determining compliance with loading in the utility's spent fuel pool) will be used to determine compliance with the loading curves. With some exceptions, reactor records for burnup are based on both in-core monitoring information (i.e., measurements) and core follow calculations. Nevertheless, it is recognized and understood that the burnup value developed and provided by a nuclear utility has some associated uncertainty. Reviews of the accuracy of reactor record assigned burnup values for commercial SNF assemblies indicate that the uncertainty in these values is less than 5% (Massie 2004, EPRI 1999). Therefore, a conservative uncertainty value (in terms of reactivity) of 5% is assigned to the reactor burnup record. This 5% uncertainty is accommodated by adjusting the criticality loading curve (i.e., increasing the minimum burnup requirement by 5%). This increased burnup requirement (to accommodate uncertainty in the reactor burnup record) is compared to the utility assigned burnup value. Note that although the methods used to calculate and verify assembly burnup values are documented in procedure form in NRC-approved technical specifications, these methods and the record keeping methods of nuclear utilities are not uniform. In a few cases, some SNF assemblies may have assigned burnup values that are averages for a batch of assemblies with similar characteristics. In such cases, an additional step will be required to convert the batch-average burnup value to assembly specific burnup values prior to the assemblies being considered for loading into a waste package.

The utility records include the assembly identifier, initial ^{235}U enrichment, and time of discharge from the reactor as well as the assigned burnup, but the distribution of burnup axially along the assembly length is not provided. The axial burnup profile is maintained within acceptable bounds by the operating conditions of the nuclear reactor and is calculated during preparations to reload a reactor, but the actual burnup profile is not measured. It is well-known that the axial burnup profile is important to the determination of the reactivity of a commercial SNF. Hence, an evaluation of several thousand calculated axial burnup profiles was performed to determine conservative, burnup-dependent, axial profiles (BSC 2003b) that are used in the determination of the loading curves. To ensure conservatism with respect to criticality, these conservative profiles are assigned to all SNF assemblies in the waste package analysis. Thus, there are no requirements for physical measurement of the axial burnup profile.

The assembly identifier is legible on each SNF assembly, and the utility records provide the associated characteristics of the assembly, including a reliable value for the assigned assembly burnup. The conservative methodologies used to determine the criticality loading curve for a TAD, which includes a 5% allowance to account for uncertainty in utility assigned burnup, provide sufficient margin so that criticality control is assured. The conservative approaches used to develop and apply the criticality loading curve are sufficiently robust that the utility assigned burnup is an adequate source of burnup values, and additional means of verification of assigned burnup through physical measurements are not needed. Nevertheless, the probability of exceeding the critical limit as a result of loading a fuel assembly with insufficient burnup is evaluated in *CSNF Loading Curve Sensitivity Analysis* (SNL 2008d) and included in the determination of the total probability of criticality in the repository.

2.2.1.4.1.2 Processes Affecting Probability of Criticality

The design for the repository incorporates multiple features that are both redundant and diverse to minimize the potential for conditions conducive to criticality. Separate features that act to isolate the fissionable material from water (moderator) accumulation and/or contact are an example of redundant features. The combination of a feature that impedes or limits the amount of water ingress into a waste package and a feature that contains neutron-absorbing materials provides diverse features for controlling criticality (e.g., borated stainless steel plates inside the waste package absorb neutrons while the waste package prevents water from entering the waste package). Therefore, for a nuclear criticality event to be credible in the repository, a very improbable combination of FEPs must occur that lead to material and geometric reconfigurations conducive to criticality. Material considerations involve the amount of fissile material (e.g., ^{235}U and ^{239}Pu), the amount of neutron-absorbing materials (e.g., boron or gadolinium), and the presence of a moderating material (e.g., water) (SNL 2008e, Section 6.2). As the amounts and presence of these materials change, the geometry necessary to achieve criticality also changes, and vice versa (BSC 2004d, Section III.3.5). The optimum geometry for a criticality event is a sphere, and, as the system geometry changes from a sphere, typically more fissile or moderator materials or less neutron absorber materials (or some combination thereof) are required for criticality. As stated in Section 2.2.1.4.1, it is important to note that the majority of the waste form types that will be emplaced in the repository (e.g., commercial spent nuclear fuel) have been discharged from a nuclear reactor because their material composition and amount of fissile material are no longer effective in supporting criticality.

During design, criticality analyses are performed to demonstrate that the initial emplaced configuration of the waste form remains subcritical, even under flooded conditions (YMP 2003, Section 1.1). Therefore, for criticality to occur inside the waste package, all of the following must occur (SNL 2008e, Section 6.2): (1) immediate or delayed waste package damage (barriers breached); (2) presence of a moderator (i.e., water); and (3) the materials inside the package must degrade and/or reconfigure (e.g., separation of fissionable material from the neutron absorber material or lack of absorber material). For criticality to occur outside the waste package, there must be a sufficient accumulation of a critical mass of fissionable material.

Water, silica, and carbon are the only potential moderating materials for internal configurations available within the repository. Water, which can enter the waste package as seepage flow or humid air, is the most effective neutron-moderating material. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the repository rock. Silica can also be introduced into the waste package through entrainment in and precipitation from the seepage flow. Carbon is present in less than 20% of the DOE SNF waste package types (SNL 2008e, Section 6.3) and then in only limited amounts, with the exception of DOE-6 fuel which is contained within a graphite matrix, but poses no criticality concern as additional absorber material in the canister is not necessary for criticality control (Radulescu, Moscalu et al. 2004, Section 10.8.6). Furthermore, there is no known mechanism for lateral transport of any carbon in the invert to alternate accumulation sites. Thus, carbon has an insignificant impact on the overall potential for criticality in the repository. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron-absorber materials take into account the presence and effect of glass and silica moderation from degraded glass in DOE SNF waste packages (SNL 2008e, Section 6.3). Silica is a much less effective moderator than water, and its introduction into commercial SNF waste packages from seepage infiltration will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality. Additionally, silica can act as a neutron reflector. However, inside the waste package, its reflector effects, which increase reactivity, are secondary to its water-displacement effects, which decrease reactivity.

For criticality to occur external to the waste package, the proper material and geometric configuration are still necessary. Since this must involve the transport and accumulation of materials with the presence of sufficient moderator in a favorable geometry, the probability of an external criticality event is expected to be lower than the probability of an in-package criticality event because of the difficulty inherent in achieving the requisite conditions as discussed below.

2.2.1.4.1.3 Screening Evaluations

The possibility of criticality in three locations was evaluated using the disposal criticality analysis methodology: in-package intact and degraded, near-field, and far-field. These repository locations are discussed in Section 2.2.1.4.1.3.1, 2.2.1.4.1.3.2, 2.2.1.4.1.3.3, and 2.2.1.4.1.3.4, respectively, and in more detail in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e, Section 6).

As stated in Section 1.5.1, the repository is designed for 70,000 MTHM consisting of SNF and HLW. This inventory consists of a diverse collection of waste form designs and compositions with the DOE SNF being the largest contributor to the waste form diversity. As indicated in Section 1.5.1.3.1.1, there are several hundred distinct types of DOE SNF. For criticality analyses, the several hundred distinct types are grouped into nine DOE SNF criticality groups as listed in Section 1.5.1.3.1.1.3, Table 1.5.1-23, and Table 2.2-12.

Within each of the nine DOE SNF criticality groups, a single fuel design was selected as being representative of the remaining fuel within each group (Section 1.5.1.3.1.1.3). The term representative means that all fuels would perform similarly regarding chemical interactions within the waste package and basket, and that canister loading limits from the representative fuel (ranges of key parameters important to criticality such as linear fissile loading and total fissile mass) are established, for which other fuels within the group can be shown to not exceed. Waste forms within a single criticality group that have configurations or key criticality parameters outside the range of applicability of the representative fuel, will require supplemental analysis and/or additional reactivity control mechanisms (Section 1.5.1.3.1.1.3). The nine DOE SNF waste form groups and the representative fuel design evaluated for each group along with the expected waste package emplacement inventory by waste form are identified in Table 2.2-12.

Detailed criticality analyses for screening justifications have been completed for the 21-PWR, 44-BWR, and a representative fuel design (identified in Table 2.2-12) for each of the nine DOE SNF groups. Naval SNF designs are addressed in the Naval Nuclear Propulsion Program Technical Support Document, Section 1.5.1.4. Commercial SNF representative analyses for degradation and reconfiguration of structural internals and the waste form are provided in *CSNF Loading Curve Sensitivity Analysis* (SNL 2008d) and *Commercial Spent Nuclear Fuel Igneous Scenario Criticality Evaluation* (SNL 2007d). Representative calculations for the degradation and reconfiguration of structural internals and DOE SNF in a waste package have been addressed in numerous analyses for the various DOE SNF fuel types. These results are summarized in *DOE SNF Phase I and II Summary Report* (Radulescu, Moscalu et al. 2004), *Intact and Degraded Mode Criticality Calculations for the Codisposal of TMI-2 Spent Nuclear Fuel in a Waste Package* (BSC 2004a), and *Intact and Degraded Mode Criticality Calculations for the Codisposal of ATR Spent Nuclear Fuel in a Waste Package* (BSC 2004b). The results indicated that the maximum k_{eff} of the various configurations is less than the critical limit. Several of the DOE fuel types incorporate neutron poison that is necessary for criticality control for certain degraded scenarios. The likelihood of the failure of quality checks that prevent accepting canisters without the shot type of absorber material is considered insignificant since such errors can be readily detected by weight measurements. However, a misload of neutron absorber material in a DOE SNF canister is possible during canister fabrication and the probability (discussed in Section 2.2.1.4.1.3.1) of such a misload is evaluated in a similar manner as absorber misloads for commercial SNF canisters (SNL 2008e, Section 4.1.15). The DOE SNF waste forms that require plate type neutron absorber materials are DOE1 (MOX), DOE2 ($UZrH_x$) (Radulescu, Moscalu et al. 2004, Executive Summary), and DOE7 (aluminum based) (BSC 2004b, Section 6.2.1).

Representative waste forms, including commercial SNF, DOE1, DOE3, and DOE9 have been evaluated in detail for the external criticality scenarios. Commercial SNF is evaluated as it represents the majority of the waste to be disposed of and is indicative of the degradation and accumulation processes involved with oxide waste forms. TMI (DOE9) is a subset of oxide waste forms and represents oxide fuel that has been significantly degraded. N Reactor (DOE3) fuel represents metal waste forms, which makes up over 80% by mass of the DOE SNF waste inventory, and FFTF (DOE1) represents MOX waste forms. In total, these 3 DOE waste forms make up approximately 90% of the metric tons of heavy metal in the DOE SNF inventory expected to be emplaced in the repository (SNL 2008e, Section 4.1.15).

Probability values associated with the various events that would be required to happen for criticality potential are provided in the following sections with the details of the calculations used to determine the upper bound probability values for the criticality FEP scenarios provided in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e, Section 6). Overall, the Criticality Event Class probability, which is the total of the 16 criticality FEP probabilities, is compared against the screening criterion in proposed 10 CFR 63.342 (SNL 2008e, Section 1.2). Therefore, if the Criticality Event Class probability is below the screening criterion, then all of the 16 criticality FEPs probabilities will also be below the screening criterion.

2.2.1.4.1.3.1 Potential In-Package Intact Configurations

The analysis of the probability of criticality for the in-package intact condition evaluates the configurations in which there are fissile materials inside waste packages that have not experienced degradation, deterioration, or alteration of their systems, structures, or components. Configurations for both nominal and initiating event cases are considered in the analysis. The in-package intact configurations are summarized in descriptions of the criticality FEPs 2.1.14.15.0A, 2.1.14.18.0A, 2.1.14.21.0A, and 2.1.14.24.0A in Table 2.2-5 and more fully in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e, Section 6).

The in-package intact configuration addresses events such as internal fabrication errors, neutron absorber misloads, and waste form misloads without degradation to evaluate those events for criticality potential and to account for their probability of criticality. The criticality FEPs screening analysis for in-package intact configurations concluded that these configurations have an insignificant potential for criticality (SNL 2008e, Section 7.3) (Table 2.2-8) primarily because there is no mechanism to accumulate sufficient amounts of moderator to support criticality.

2.2.1.4.1.3.2 Potential In-Package Degraded Configurations

The analysis of the probability of criticality for the in-package degraded condition evaluates the configurations in which there are fissile materials inside waste packages that have experienced degradation, deterioration, or alteration of their systems, structures, or components. Configurations for both nominal and initiating event cases are considered in the analysis. The in-package degraded configurations are summarized in descriptions of the criticality FEPs 2.1.14.16.0A, 2.1.14.19.0A, 2.1.14.22.0A, and 2.1.14.25.0A in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e, Section 6).

In-package degraded configurations with potential for criticality were identified using the disposal criticality analysis methodology. These configurations include various states of degraded waste forms, fabrication errors, neutron absorber misloads, and waste form misloads. The results from the screening analysis for the criticality FEPs for in-package degraded configurations (summarized below) showed that the probability of an in-package criticality event from these configurations is below the probability criterion for event inclusion specified by proposed 10 CFR 63.342(a) (Table 2.2-8).

Table 2.2-8 shows the probability of potential criticality for the initiating event scenarios. The values listed are the sum over the suite of waste package and waste form combinations for the three locations. Note rockfall (FEP 2.1.07.01.0A) has been screened from performance assessment on the basis of low consequence (SNL 2008a) which is not directly applicable to criticality potential evaluations. Rock block sizes generated from nominal (nonseismic) processes are not sufficient to tear or rupture the drip shield plates (Section 2.3.4.1; SNL 2008a, FEP 2.1.07.01.0A, Rockfall), therefore, it is concluded that nonseismic rockfall cannot initiate a breach of the waste package and has an insignificant contribution to the probability of potential criticality. The sum of the probabilities of potential criticality associated with the initiating event scenarios for each waste package type is shown in the bottom right of Table 2.2-8 and represents the total probability of criticality for the repository over the 10,000-year period following repository closure.

For the in-package degraded configuration scenarios, the internals are degraded and the cladding is considered breached within a failed waste package and the interior of the fuel rods are exposed to the repository environment. As the temperature of the repository decreases after the initial thermal spike, the relative humidity to which the commercial SNF matrix will be exposed will increase and is expected to approach 100% when the temperature decreases to 100°C and lower (SNL 2008f, Figure 7.5-6, Section 7.5.2.5). The plausible mechanisms for waste form degradation are discussed in detail in *CSNF Waste Form Degradation: Summary Abstraction* (BSC 2004f, Section 6.2.2), but these discussions indicate that the overall oxidative dissolution process involves a coupled series of redox, surface complexation and dissolution, and precipitation reactions depending on the fluid environment (water film on the fuel surfaces). Upon contact with air-saturated condensate (i.e., water), UO_2 and commercial SNF are expected to undergo reactions of the following type to form dehydrated schoepite and metaschoepite:

$$UO_2\,(s) + \tfrac{1}{2}\,O_2\,(aq) + 0.8\,H_2O\,(l) = UO_3\;0.8H_2O\,(s)$$
$$UO_2\,(s) + \tfrac{1}{2}\,O_2\,(aq) + 2\,H_2O\,(l) = UO_3\;2H_2O\,(s) \qquad \text{(Eq. 2.2-2)}$$

Schoepite is also demonstrated to be the most likely uranium mineral to form based on thermodynamics in *Geochemistry Model Validation Report: Material Degradation and Release Model* (SNL 2007b, Section 6.3.16; pp. 6-37, 6-47; Appendix E). Other uranium minerals may form in smaller quantities, such as uranophane and boltwoodite (SNL 2007b, p. 6-47, Appendix E). Studtite is also in the thermodynamic database that is utilized in *Geochemistry Model Validation Report: Material Degradation and Release Model* (SNL 2007b) but is not predicted to form because it requires a significant presence of hydrogen peroxide (H_2O_2) prior to formation (SNL 2007e, Section 6.7.2.1). The occurrences of studtite and metastudtite in certain natural environments and in laboratory radiolysis experiments, as discussed in Section 2.3.7.11.2.1, do not affect this conclusion. The very rare appearances of these minerals in degrading UO_2 deposits are thought to result from radiolysis occurring in microenvironments with little or no contact with the atmosphere where high concentrations of H_2O_2 could develop over long periods. The laboratory experiments were carried out at far higher alpha fluxes than expected from waste or on solutions that were not in contact with the atmosphere. Neither case is analogous to the conditions at Yucca Mountain. This being the case, studtite is not likely to form in the Yucca Mountain environment, in which waste degrades in contact with the atmosphere (SNL 2007e, Section 6.7.2.1).

Each scenario event sequence that leads to internal degradation will result in different internal degraded configurations. There is a high degree of variability in the possible configurations that could develop as well as other uncertainties in the values of particular parameters needed to fully define how the configurations would develop. The design basis configuration developed in *CSNF Loading Curve Sensitivity Analysis* (SNL 2008d) and described in Section 2.2.1.4.1.1.2 has been determined to bound the various limiting configurations that would result for each of the criticality FEP scenarios (nominal, rockfall, seismic, igneous). A review of the scenarios and configurations with potential for criticality evaluated in *Configuration Generator Model* (BSC 2004c) has identified two dominant leitmotivs common to each of the in-package scenarios in sequences of events that must occur for a criticality event to be credible. *Screening Analysis of Criticality Features, Events, and Processes* (SNL 2008e, Section 1) and *CSNF Loading Curve Sensitivity Analysis* (SNL 2008d, Section 6) indicate that full scenario development cannot be performed with sufficient precision to generate meaningful results. Therefore, an upper bound on the probability of criticality is calculated where focus is placed on conditions necessary for criticality, and additional probabilities associated with various environmental conditions and degradation mechanisms are truncated. This is acceptable and conservative because the additional probabilities that are included are less than 1.0 and would result in a monotonically decreasing value of the overall probability for the sequence.

Two independent events, occurring in conjunction with an initiating event that causes a waste package breach, have been identified as the primary contributors to the potential for criticality: (1) absorber material misload; and (2) waste form misload. These independent events, coupled with the probability of an initiating event that could result in breaching the waste package, provide an upper bound estimate for the probability of achieving a configuration with potential for criticality. An upper bound is provided because, for independent event (1) absorber material misload–the probability of criticality is conservatively set to the maximum value (i.e., 1.0) within the sequence of events that make up the scenario. For independent event (2) waste from misload–the calculated probability of a criticality from a waste form misload is based on a bounding design basis configuration that maximizes reactivity potential, whereas the actual scenario class limiting configuration would be a less reactive configuration than the design basis configuration, thus having a lower increase in reactivity from a waste form misload. Since the two misload events are independent, the end probability values from each sequence are additive. As stated above, including probabilities from additional events within these sequences can only result in decreasing the probability of criticality. This is because the additional event probabilities are multipliers within the sequence, and would be less than 1.0 (and most, much less than 1.0). Hence, inclusion of these additional probabilities can only further reduce the calculated probability of criticality.

Installing improper absorber material in a canister is a fabrication related error. This type of event can only occur during fabrication and/or loading of a canister and is similar to waste package early failure mechanisms (SNL 2007f, Section 6.2). The neutron absorber misload event represents the improper performance of the neutron absorber plates due to fabrication related errors (e.g., incorrect material installed during fabrication or absorber content of plates outside specified range). Fabrication and operational process errors are evaluated using the waste package early failure mechanisms (Section 2.3.6.6.3.2) as surrogates for such initiating events. These types of events can only occur during fabrication and/or loading of a canister due to process or procedural errors and are similar to waste package and drip shield early failure mechanisms (SNL 2007f, Section 6.2). Errors in fabrication and operational processes are primarily due to human factors that are common to the various processes. Surrogate fabrication and operational processes with associated human factor errors have been evaluated in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (SNL 2007f), and results are used for such initiating events for the waste package and drip shield early failure mechanisms. The mean value of the probability distribution for a fabrication related failure (failure to install the proper material) is given as 1.25×10^{-7} per canister (Section 2.3.6.6.3.2.1). Note that not all DOE SNF canisters use absorber plates for criticality control. Several of the DOE SNF fuel types incorporate neutron absorber that is necessary for criticality control for certain degraded scenarios. The neutron absorber is provided by basket material made of a nickel-gadolinium alloy and/or gadolinium-bearing shot composed of iron or aluminum. The DOE-owned SNF waste forms that require plate type neutron absorber materials (DOE 2004, Sections 3.1.4 and 3.1.5) are mixed oxide (MOX), represented by the Fast Flux Test Facility (FFTF) fuel, $UZrH_x$, represented by Training, Research, Isotopes, General Atomic (TRIGA) fuel, U/Th Oxide, represented by Shippingport Light Water Breeder Reactor (LWBR) fuel, aluminum-based DOE-owned SNF, represented by Advanced Test Reactor (ATR) fuel, and U-Zr/U-Mo, represented by Enrico Fermi fuel (DOE 2004, Section 2.1.11). The absorber material for the Shippingport LWBR and Enrico Fermi SNF waste forms consists of shot and, thus, the absorber misload probability is considered insignificant. Thus, the MOX, ATR, and TRIGA waste forms are the only ones for which configurations with criticality potential have a nontrivial probability of absorber misload.

An analysis of commercial SNF misload probabilities is documented in *Commercial Spent Nuclear Fuel Waste Package Misload Analysis* (BSC 2003c). Results from this analysis establish that the probability of a loading curve violation in a 21-PWR Absorber Plate Waste Package is 1.18×10^{-5} (BSC 2003c, Table 41). The TAD canister specifications require the canisters for PWR SNF to contain 21 assemblies similar to the 21-PWR Absorber Plate Waste Package (SNL 2007g, Section 4.1.1.2). The cited analysis is used as a surrogate for misloading waste forms in a TAD canister since the misloading of an assembly into a TAD canister requires the same improper selection of an assembly with characteristics (burnup and enrichment) in the unacceptable range of the loading curve. Thus, the probability of a loading curve violation for TAD canisters is expected to be similar in magnitude to the 21-PWR Absorber Plate Waste Package value (SNL 2008e, Section 6.3.2). However, neighboring assemblies that have lower reactivity values may provide partial compensation for the excess reactivity from the incorrectly loaded assembly. Given that a PWR assembly misload occurs, the likelihood of the misloaded configuration having potential for criticality has been shown to be 0.014 from results of a probabilistic calculation of that potential (SNL 2008d, Section 7). The probability of water being present is conservatively set to 1.0 (SNL 2008e, Section 6.2.1) because the relative humidity in the drifts is expected to approach 100% (SNL 2008f, Figure 7.5-6), and, without an adequate amount of water, the probability of criticality is insignificant.

The probability of misloading assemblies in the 44-BWR TAD canister is insignificant because the selected BWR inventory for the repository is in the acceptable region of the loading curve map (SNL 2008d, Section 6.3.3). In the event that BWR assemblies are identified on the unacceptable side of the loading curve, the probability of criticality from this is expected to be much less than that calculated for PWR waste packages, resulting in an insignificant contribution to the overall probability of criticality. Misloading of waste forms in codisposal waste packages is very improbable (SNL 2008e, Section 6.3.2) because the shape of the defense HLW glass canisters differs significantly from the DOE SNF canisters and the various DOE waste forms also differ significantly in size and shape (Radulescu, Moscalu et al. 2004, Sections 2 and 3; Smith and Loo 2007, Section 5.2) (Figures 1.5.1-8 and 1.5.1-9). Thus, the waste forms and canisters can be readily distinguished by visual inspection and misloading of waste forms in DOE SNF canisters or misloading the canisters into codisposal waste packages is considered to be very improbable. Therefore, the waste form misload probability for codisposal waste packages is considered to be insignificant.

Sensitivity studies have shown that the commercial SNF waste form in various degraded configurations such as saturated porous schoepite does not result in a more reactive configuration than the design basis configuration (SNL 2008d, Section 7). This indicates that assembly misload is the most likely waste form configuration with potential for criticality. The probability of a potentially critical configuration resulting from an assembly misload of a 21-PWR TAD canister is $0.014 \times 1.18 \times 10^{-5} = 1.65 \times 10^{-7}$ per canister (SNL 2008e, Section 6.3.2). Note that this probability is derived from preclosure activities which makes it independent of the postclosure time period.

The probability for the occurrence of configurations with potential for criticality is evaluated from a number of independent sets of sequences of events where all of the events in any specific sequence must happen for that configuration to occur. Since the events in any one sequence can also be considered as independent entities, the probability of the sequence is the product of the probability of each individual event. The expected probability of having a particular sequence occur in exactly k waste packages in the repository is a Binomial process described by the Binomial probability distribution, $P_B(n; p, N)$, with probability p for occurrence in a waste package and $q = 1 - p$ for nonoccurrence. The probability of having the sequence occur in at least "k+1" waste packages is given by

$$P(\text{at least } k+1 \text{ items occur}) = 1 - \Sigma_{l=0,k} P_B(l; p, N) \qquad \text{(Eq. 2.2-3)}$$

where

k	=	number of items affected (e.g., waste packages, drip shields)
p	=	probability for occurrence of the event
N	=	number of possible items involved.

For large N and small p where $N \times p \cong \lambda$, the Binomial distribution converges to the Poisson distribution with a mean of $\lambda = N \times p$. Then Equation 2.2-3 can be written as:

$$P\ (\textit{at least}\ k + 1\ \textit{waste packages}) = 1 - \Sigma_{l=0,k} P_P\ (l;\ N \times p) = 1 - \Sigma_{l=0,k} \frac{\lambda^l \times \exp(-l\lambda)}{l!} \qquad \text{(Eq. 2.2-4)}$$

The probability for the occurrence of a criticality event sequence for any waste package in the repository (which can be stated as the probability of having at least one such sequence occur) is given by Equation 2.2-4 with $k = 0$. For the case where $k = 0$ and λ is small, Equation 2.2-4 can be approximated by λ. Then the probability of at least one waste package configuration with criticality potential occurring in the repository is given by λ ($= N \times p$).

In the following scenarios, the various SNF types have been evaluated for criticality potential by considering the design basis configuration in lieu of attempting to evaluate a range of specific environmental parameters and configurations, along with an estimate of their probability of occurrence, which could generate a large number of possible event sequences and outcomes. The design basis configuration (Section 2.2.1.4.1.1.2.1) used for development of the respective loading curves, PWR or BWR, is considered bounding in terms of criticality potential of the potential configurations that would result from natural degradation processes following an initiating event. Therefore, the probability of criticality calculated for this configuration will bound the probability of a less reactive configuration (SNL 2008e, Section 6.2).

2.2.1.4.1.3.2.1 Nominal Scenario In-Package Degraded Configuration

The initiating event for this nominal case scenario is the failure of the low-plasticity burnishing process such that the compressive stress layer in the waste package outer corrosion barrier closure lid is not produced, processes for stress mitigation in the waste package outer corrosion barrier fail, or a drip shield is misplaced. Weld flaws in the waste package outer corrosion barrier lid or a failure of the stress mitigation processes can lead to a waste package breach from either weld flaw propagation or stress corrosion cracks initiated by the residual stresses. A drip shield emplacement error could result in an advective flow path to the waste package outer corrosion barrier creating an environment for subsequent localized corrosion processes that could breach the waste package outer corrosion barrier. These events are analyzed in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (SNL 2007f, Section 6.3.5) and discussed in Section 2.3.6. If a flaw approximately normal to the circumferential tensile stress exists, stress corrosion cracking can occur because the weld flaw is a stress corrosion cracking initiator. The propagation rate for stress corrosion cracking in Alloy 22 is given in *Stress Corrosion Cracking of Waste Package Outer*

Barrier and Drip Shield Materials (SNL 2007h, Table 6-6 mean) as 1.1×10^{-9} mm per second, which will penetrate the 25 mm thick waste package in less than 1,000 years, causing a breach.

The mean value for the probability that a waste package outer corrosion barrier has an early failure is 1.13×10^{-4} per waste package (Section 2.3.6.6.3.2.7) and the mean probability value for improper emplacement of a drip shield is given as 4.36×10^{-9} per drip shield (Section 2.3.6.8.4.3.2.4). Because these events are all associated with operations during the preclosure period, the probability is constant over the initial 10,000-year postclosure time period. Note that failure of the stainless steel inner barrier and TAD/DOE canister has been assigned a probability of 1.0 for this event sequence (i.e., no credit is taken for their presence). The calculated probability of in-package criticality resulting from a nominal scenario degraded configuration is discussed in detail in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e, Section 6.3.2) and provided in Table 2.2-8.

The reported value is developed by exercising Equation 2.2-4 with the probability values described above as follows:

- PWR TAD canister loading curve violation:

  $\{1\text{-}P_B\ (0; ((1.13 \times 10^{-4}) \times 1.65 \times 10^{-7}), 4{,}568)\} = 8.5 \times 10^{-8}$

- PWR TAD canister absorber misload:

  $\{1\text{-}P_B\ (0; ((1.13 \times 10^{-4}) \times 1.25 \times 10^{-7}), 4{,}568)\} = 6.5 \times 10^{-8}$

- 44-BWR TAD canister absorber misload:

  $\{1\text{-}P_B\ (0; ((1.13 \times 10^{-4}) \times 1.25 \times 10^{-7}), 2{,}915)\} = 4.1 \times 10^{-8}$

- DOE SNF canister absorber misload (DOE1, DOE2, and DOE7 in Table 2.2-12):

  $\{1\text{-}P_B\ (0; ((1.13 \times 10^{-4}) \times 1.25 \times 10^{-7}), 1{,}223)\} = 1.7 \times 10^{-8}$

The sum of these probabilities provides the total probability for the nominal case in-package location.

2.2.1.4.1.3.2.2 Seismic Scenario for In-package Degraded Configuration

The seismic disruptive event is described in Sections 2.2.2.1 and 2.3.4. This section describes what has been considered for criticality potential evaluations. Vibratory ground motion, faulting, and rockfall induced by a seismic event are potential initiating events that could cause waste package or drip shield damage or drip shield failure leading to subsequent waste package failure from localized corrosion (SNL 2008a, FEP 2.1.03.03.0A, Localized corrosion of waste packages). Such damage and/or failure may allow the influx of water (either advective or diffusive) into the waste package, which, in turn, has the potential to initiate processes leading to configurations with potential for criticality.

As discussed in Section 2.3.4.5.1.2, seismic induced impacts by large rock blocks in unfilled or partly filled drifts in nonlithophysal units may deform the drip shield and/or fail the plates and axial stiffeners on the crown of the drip shield. Failed plates provide a potential pathway for seepage through the drip shield. If the drip shield collapses from a rock block impact, the waste package may also be damaged or ruptured from the impact. This mechanism has been examined and excluded as a result of low consequence from performance assessment (SNL 2008a, FEP 1.2.03.02.0B, Seismic-induced rockfall damages EBS components) but must be evaluated as a potential initiating event for waste package breach. A large block analysis indicated that waste package damage could occur for the most severe events involving rock Block 1 (SNL 2007i, Section 6.4.7.3) (Table 2.3.4-34) characterized by a rock block mass of 28.29 metric tons at a peak ground velocity (PGV) level of 5.35 m/s (Table 2.3.4-34), which is beyond the bounding ground motion level of 4.07 m/s considered for the performance assessment. The maximum displacement expected for drip shield stiffeners from an impact of rock Block 1 (28.29 metric tons) is 20.4 cm (Table 2.3.4-36). When compared to the initial clearance between the drip shield and the waste package of 36 cm (Table 2.3.4-50), no initial contact between the drip shield and the waste package is predicted from the impact. However, the impact may fail the drip shield stiffeners and it is possible that deformation of the drip shield will continue such that contact is made with the waste package but at a substantially reduced velocity. Because the PGV that could potentially generate enough impact energy to fail the drip shield stiffeners is beyond the bounded PGV, this waste package breach mechanism doesn't need to be evaluated further. For all other cases, including rock Block 2 (7.49 metric tons) at a PGV level of 1.05 m/s, the maximum stiffener displacement is 4.2 cm (Table 2.3.4-36) with no expectation of damage to the waste package outer corrosion barrier.

The effects of vibratory ground motion depend on the condition of the components and the in-drift environment (SNL 2007j, Section 6.1.2). The predominant mechanism for damage is seismically-induced impact between EBS components. Under significant vibratory ground motions, impacts may occur between adjacent waste packages, between a waste package and its pallet, and between waste packages and the surrounding drip shield. It was concluded that most of the damage to waste packages would be caused by the waste package-to-pallet impacts.

Stress corrosion cracking from high residual stress is considered to be the cause of waste package damage from impact processes under vibratory ground motion (Section 2.3.4). Regions where the residual stress from mechanical damage exceeds the tensile failure criterion are expected to be severely cold-worked and, hence, potentially subject to enhanced stress corrosion cracking. However, if cracking were to occur as a result of specific environmental conditions coincident with the mechanical deformation, cracks would take time to develop after the shaking event causes a change in loading.

This sequence of events begins with the occurrence of a seismic vibratory ground motion event. The probability of a seismic event is a random event in time following a Poisson distribution (Section 2.3.4.5) which increases linearly in log-time. If a seismic vibratory ground motion event occurs, the estimated probability of damage to a TAD canister waste package from impacts is given as 0.118 and 0.0 (Table 2.3.4-29) at the 90% residual stress threshold (RST) level for a 4.07 m/s PGV and a 2.44 m/s PGV, respectively. These PGVs occur with a mean annual probability of exceedance of 4.5×10^{-7} for 2.44 m/s PGV and 10^{-8} for 4.07 m/s PGV (Section 2.3.4.3.2.4). Exercising Equation 2.2-3, which converges to Equation 2.2-4 for $k = 0$,

$p = 1.0 \times 10^{-8} - 4.5 \times 10^{-7}$, and $N = 10{,}000$ years to determine the probability of at least one package breaching is as follows:

$$\text{P (of at least 1 seismic event of sufficient magnitude for required PGV)} = 4.4 \times 10^{-3}$$

Taking the product of the probability of the seismic event and the probability of damage $4.4 \times 10^{-3} \times (0.0 + 0.118)/2 = 2.6 \times 10^{-4}$. Because the probability of damage values (i.e., 0 and 0.118) are point estimates evaluated at discrete PGV levels, the probability over the seismic damage frequency range is assigned the average value. Note that this value is a factor of 5 greater than what is calculated in Section 2.4 which uses a more detailed calculation to sample from a distribution of RST values between 90% and 105% rather than bounding the probability by using only the 90% RST value. The same process is followed for the codisposal package using the information provided in Table 2.2-13 and Table 2.3.4-30, which are summed over the different PGV ranges to produce a probability of damage for a codisposal package of 0.24. Note that this value is a factor of 3 greater than what is calculated in Section 2.4 which uses a more detailed calculation to sample from a distribution of RST values between 90% and 105% rather than bounding the probability by using only the 90% RST value.

Details of the calculations are provided in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e, Section 6.4.2).

Seismic events can also result in failure of a drip shield caused by rockfall which may lead to an advective flow path to the waste package that could result in localized corrosion (waste package failure). Note that tearing or rupture of the drip shield plates from large block impacts in the nonlithophysal zone has been screened from the performance assessment because of low consequence (SNL 2008a, FEP 1.2.03.02.0B, Seismic-induced rockfall damages EBS components), which is not directly applicable to criticality potential evaluations. Drip shield failure could result in an advective flow path to the waste package outer corrosion barrier, creating an environment for subsequent localized corrosion processes that could breach the waste package outer corrosion barrier. Therefore, this must be considered as an initiating event that can lead to a potentially critical configuration. Localized corrosion in the form of pitting and crevice corrosion can occur on exposed surfaces of the waste package outer corrosion barrier provided an appropriate aqueous environment is present (SNL 2008a, FEP 2.1.03.03.0A, Localized corrosion of waste packages). Seepage water through ruptured drip shields can provide the basis for such an environment to develop. Two rockfall initiating events are considered for failure modes of the drip shield - single large rock block impacts and drift collapse resulting in drip shield overload. Development of an estimate of the mean probability that at least one waste package in the target group (e.g., commercial SNF packages) is emplaced in the nonlithophysal zone at a location where the drip shield is ruptured by a seismically induced impact from a large rock block, or in the lithophysal zone where drift collapse results in drip shield rupture, and where there is seepage, and that seepage initiates localized corrosion of the waste package outer barrier, during the first 10,000 years after closure, is provided in *Waste Package Flooding Probability Evaluation* (SNL 2008g). The combined probability of drip shield rupture from a seismic vibratory event resulting in localized corrosion of the waste package outer barrier for both the lithophysal and nonlithophysal units is less than 4.2×10^{-5} and 2.2×10^{-5} per commercial SNF package, respectively, and less than 2.8×10^{-5} and 9.6×10^{-6} for the lithophysal and nonlithophysal units, respectively, for the codisposal waste package over 10,000 years.

A seismic event can also induce fault displacement that can potentially result in drip shield and waste package failure for those structures intersecting the fault, which can then potentially allow advective and/or diffusive flow into the waste package and lead to conditions conducive to criticality. Additionally, new fractures that intersect the drift segments and the collapse of the drift due to a seismic event will have an effect on the seepage as to both location and rate. However, these changes in seepage have no impact on the repository's potential for criticality without drip shield failure resulting from fault displacement.

Seismic events that can cause significant displacement (>0.1 cm) along fault lines that do intersect the drifts have a low probability of occurrence (i.e., mean annual exceedance frequencies of less than about 10^{-6} per year) (Tables 2.3.4-54 and 2.3.4-55). Damage to the drip shield causing loss of function is not expected to result from seismic faulting until sufficient displacement occurs to make contact between the drip shield and the drift. The number of failed waste packages increases with increasing seismic energy (decreasing annual exceedance frequency) to a maximum number that depends on waste package design variants (Section 2.3.4). The exceedance frequency range per year for the commercial SNF TAD and codisposal waste packages is subdivided into multiple ranges, depending on the waste package design variants. The initiating event for this scenario is a seismic event with an annual exceedance frequency ranging between 2.5×10^{-7} to 10^{-8} per year (Table 2.3.4-59).

In order to calculate an upper bound to the probability of potential criticality resulting from a seismic initiating event, consideration is required of the following probabilities resulting in waste package breach:

1. Probability of a seismic vibratory ground motion event
2. Probability of waste package outer corrosion barrier damage from effects of the ground motion
3. Probability of drip shield failure
4. Probability of seepage collocated with the drip shield failure
5. Probability of localized corrosion occurring from the seepage
6. Probability of fault displacement damaging drip shield and waste package.

The combined probabilities for items 3, 4, and 5 were provided, above, and result in one or more waste package breaches of less than 4.2×10^{-5} over 10,000 years. The probability of item 6 is less than 2.2×10^{-3} over 10,000 years. The combined probability of items 1 and 2 were discussed above and shows that the commercial SNF breach probability is less than 2.6×10^{-4} over 10,000 years, and the codisposal outer corrosion barrier breach probability is 0.24 over 10,000 years. Based on these breach probabilities, the codisposal probability will dominate the sum of each of the independent breach probabilities.

These calculations are explained in detail in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e, Section 6.4).

The combined probability calculated by summing each of the seismic initiating event sequences resulting in outer corrosion barrier breach per waste package variant is provided in Table 2.2-8. Considering only the contribution from the codisposal waste package breach and exercising Equation 2.2-4 with the probability of absorber misload (1.25×10^{-7}) identified above in Section 2.2.1.4.1.3.2 and the number of codisposal packages using absorber plates for criticality control (1,223) (Section 2.2.1.4.1.3.2) provides a value of 3.66×10^{-5} which is equivalent to the value provided in Table 2.2-8. Note that this value is considered bounding due to the following conservatisms that are inherent in this calculated value:

- The probability of damage to the outer corrosion barrier is equal to the probability of breach of the DOE canister. Detailed seismic response evaluations have not been performed to assess the probability of damage to the DOE canister which is located in a central support tube of the codisposal waste package. Based on this geometric arrangement, the size and relatively light weight of the canister in comparison to the waste package, and the internal basket structure within the DOE canister, additional resistance to breach is expected that is not currently credited (SNL 2008e, Section 6.4; SNL 2007j, Sections 6.1.3.2 and 6.13).

- The 90% RST limit is used for when breach occurs instead of a distribution over the range from 90% to 105%.

- Only a fraction of the 1,223 codisposal waste packages that have absorber plates installed actually need them for criticality control. In addition, for those that do need the absorber plates, significant degradation of the waste form and reconfiguration must occur before criticality is possible without the absorber plates. Typically for this to occur would require a "bathtub" within the DOE canister which would actually require an advective flow path. Having significant damage to the outer corrosion barrier and the DOE canister so that water ingress into the waste package is at a higher rate than the exit rate so that it can fill to submerge the internal DOE canister so that it can also fill is nonmechanistic but assumed to occur in this probability estimate. Additionally, water ingress for this scenario would be limited to diffusive transport. In the current assessment these are all given a probability of 1.0 of occurring in order to provide a conservative estimate of the probability of potential criticality.

2.2.1.4.1.3.2.3 Rockfall Scenario for In-Package Degraded Configuration

Three mechanisms in the repository environment have been identified as potential initiators of rockfall events in the emplacement drifts: (1) seismic vibratory ground motions; (2) thermal stress (generated by the decay heat from the emplaced waste packages); and (3) static fatigue from nominal degradation of rock (BSC 2004g, p. viii). Section 2.3.4.1 indicates that rockfall related to nonseismic processes (FEP 2.1.07.01.0A) such as drift degradation induced by in situ gravitational and excavation-induced stresses as well as thermally-induced stresses do not generate rock block sizes sufficient to tear or rupture the drip shield plates. Therefore, seismic induced rockfall is the only rockfall event that can induce significant damage to the EBS components over 10,000 years after repository closure. The probability of achieving a configuration with criticality potential in the repository resulting from a seismic vibratory induced drip shield rupture due to rockfall was discussed in Section 2.2.1.4.1.3.2.2. Rock block sizes generated from nominal (nonseismic) processes are not sufficient to tear or rupture the drip shield plates (Section 2.3.4.1); therefore, it is concluded that nonseismic rockfall does not initiate a breach of the waste package and the probability of criticality for this initiating event scenario is insignificant.

2.2.1.4.1.3.2.4 Igneous Scenario for In-Package Degraded Configuration

The igneous disruptive event is described in Sections 2.2.2.2 and 2.3.11. This section describes what has been considered for criticality potential evaluations. The mean annual frequency of an igneous intrusion event is characterized in the cited reference by a probability distribution having a mean value of 1.7×10^{-8} per year as given in Sections 2.2.2.2 and 2.3.11. The mean frequency value corresponds to a probability of 1.7×10^{-4} within 10,000 years of disposal.

For igneous intrusion, magma is expected to enter the drifts. The waste package, the canister internals, and the SNF will heat up to near magma temperatures in days to weeks exceeding 700°C for one to nineteen months, depending on the temperature of the magma and the decay heat generated by the waste (SNL 2008e, Section 6.6.1). At these high waste package temperatures, Fe-Zr and Ni-Zr liquid eutectics are expected to form (starting at approximately 948°C (ASM International 1996, Fe-Zr and Ni-Zr phase diagrams)), but are not expected to provide any mechanisms causing appreciable removal of the neutron-absorber materials from their general locale in relation to the waste form since the eutectic will contain both the absorber and waste form materials.

Temperatures will also be sufficiently high such that the DOE aluminum fuels and gadolinium-containing aluminum shot used with certain DOE fuels for criticality control are expected to melt. Thus, these configurations are susceptible to fuel and absorber material reconfiguration by melting and collecting towards the bottom of the DOE SNF canister. Basket structure slumping due to the high temperature environment from the surrounding magma, or from the formation of a mass either by melting or eutectic formation, is not expected to lead to configurations where the fissile material is concentrated away from the bulk of the neutron absorber in the canisters. Melting or eutectic formation or slumping will always provide some mixing between the fissile materials and the neutron absorber. Sensitivity evaluations have been performed in *Criticality Potential of Waste Packages Affected by Igneous Intrusion* (BSC 2006) for the DOE SNF waste form types and conclude that the calculated k_{eff} values for the representative configurations remain below the critical limits for the respective waste forms (Table 2.2-11).

In summary, it is expected that an igneous intrusion would sufficiently compromise the integrity of the waste packages, drip shields, and cladding in affected emplacement drifts to make them ineffective (i.e., a total loss of function in isolating waste packages and waste forms from seepage water when it returns after drifts have cooled). The damage to the waste packages is expected to be ubiquitous. Thus, it is improbable that a bathtub configuration (forming a closed-bottom container necessary for pooling) can be maintained or even created in a post igneous intrusion environment. However, water is expected to percolate through disrupted waste packages facilitating conversion of the fissile material to a moderated form of uranium (schoepite and metaschoepite).

The criticality potential for the in-package degraded scenario resulting from an igneous event is negligible since criticality analyses of potential configurations have shown that these configurations are less reactive than the design basis configuration (SNL 2007d, Section 7), provided that the absorber material is not misloaded and, for TAD canisters, commercial SNF assemblies have not been misloaded.

Sensitization of stainless steel and borated stainless steel can occur during heating and cooling, such as would occur from magmatic intrusion. In principle, heating of the stainless steel to magmatic temperatures might cause sensitization and a reduction in corrosion resistance. During sensitization, the chemical composition in the vicinity of the grain boundaries can be altered by the precipitation of chromium-containing carbides which depletes chromium at the edges of the adjacent alloy grains (typically austenite) and increases potential for intergranular corrosion, since the chromium-depleted regions fail to produce a chromium-oxide passivating layer. Subsequent slow cooling at 500°C to 750°C may desensitize the steel, as chromium diffuses back into the depleted zones. However, the situation at still lower temperatures is less clear, as the solubility of the carbide phase decreases. Fox and McCright (1983) argue that heating in the repository for years, at temperatures of 350°C and below, may cause desensitization, especially in Stainless Steel Type 304 alloys.

The Stainless Steel Type 304B does not suffer sensitization in the same way that Stainless Steel Type 304L is affected. The metal borides are actually boro-carbides of the form $(Cr, Fe)_2(B, C)$ or $(Cr, Fe)_{23}(B, C)_6$ and effectively soak up most excess carbon. The borides precipitate at rather high temperatures and are stable down to fairly low temperatures, so there is no formation of chromium carbide. For heat-treated Stainless Steel Type 304B, Moreno et al. (2004) conclude, "it is not possible to talk about a common sensitized state as no carbides are found at the grain boundaries." Therefore, this indicates that the chromium depletion at the grain boundaries would be minimized and thus not result in increased corrosion potential.

Regardless of the sensitization effects on the corrosion resistance of the neutron absorber material, most of the boron is expected to remain between the assemblies.

Part of the basis for this conclusion is evidence which shows that the boron in borated stainless steel has a very low solubility within the iron matrix of the steel (He et al. 2000, p. 218; Goldschmidt 1971, p. 911; Sourmail et al. 2004, p. 1275). Instead of a solid solution, the boron is present as separate chromium boride particles. These particles are not expected to dissolve into the aqueous solution during degradation of the steel but are left behind as insoluble products during corrosion (Fix et al. 2004, p. 126; Lister et al. 2007, pp. 39 to 43). In addition to the low solubility of the boron, the resultant internal configuration of the waste package is expected to limit the amount of material mobility.

The specific geometry and composition of the numerous intermediate configurations that may result as the internal components degrade and reconfigure are dependent on the environmental conditions and cannot all be defined individually for analysis. As stated above, there is a high degree of variability in the possible configurations that could develop as well as a high degree of uncertainty associated with any given scenario that may be evaluated. Considering the increased variability in the potential geometric reconfigurations, effects on material performance, and neutron spectrum changes resulting in varied neutron absorber effectiveness, calculated probability numbers are of limited value considering the high degree of uncertainty associated with any given scenario that may be evaluated. The initiating event probability for the igneous intrusive event (1.7×10^{-4}) is already a factor of 1,400 below the probability of seismic vibratory ground motion damaging the codisposal waste package (0.24) as discussed in Section 2.2.1.4.1.3.2.2, thus any contribution to the total probability of criticality from an igneous initiating event would be negligible.

2.2.1.4.1.3.3 Potential Near-Field Configurations

The near-field configuration locations for analyses using the disposal criticality analysis methodology include locations outside the waste package but within the emplacement drift where the most significant location is the drift invert below the waste package. The configurations for both nominal and initiating event scenarios are considered in the analyses. The near-field configurations are summarized in descriptions of the criticality FEPs 2.1.14.17.0A, Near-field criticality; 2.1.14.20.0A, Near-field criticality resulting from a seismic event; 2.1.14.23.0A, Near-field criticality resulting from rockfall; and 2.1.14.26.0A, Near-field criticality resulting from an igneous event, and more fully in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e, Section 6).

Near-field criticality cannot occur unless the waste package and waste form are degraded. Water infiltration is required to degrade the waste form and waste package internals, and transport fissile material to the near-field location. Criticality cannot occur unless at least the minimum critical mass of a waste form can be accumulated. The probability of an external criticality event is expected to be lower than the probability of an in-package criticality event. This is because, in addition to the events evaluated to calculate the probability of water infiltrating a breached waste package, the probability of the following events must also be considered for near-field external criticality:

- Separation of the fissile materials from the degraded waste form
- Sufficient seepage water to transport fissile materials from the waste package
- Accumulation of sufficient fissile material into a potentially critical configuration in the near-field environment.

The amount and form (solution, colloid, or slurry) of fissile material being transported out of a waste package are considered. The potential physical volumes available within the drift where fissile material could accumulate are considered. The mechanisms for accumulation of materials in the available volumes, such as precipitation, colloid sorption, and physical settling, are then considered. Calculations determine the minimum mass required for criticality, which is then compared to the maximum mass of fissile material that can accumulate in the invert volume within 10,000 years of disposal.

In the nominal scenarios, the only identified events that can breach a waste package over 10,000 years are stress corrosion cracking resulting from flaws in the outer corrosion barrier closure lid welds, undetected fabrication defects, or localized corrosion initiated by seepage flow through improperly emplaced drip shields. Water infiltration can only occur through stress corrosion cracking breaches by diffusive flow of humid air, seepage flow through cracks in both the drip shield and waste package beneath seepage drips, or condensation on the underside of the drip shield. However, flow of such condensation or leakage will be insignificant (SNL 2008a, FEPs 2.1.08.14.0A, Condensation on underside of drip shield, and 2.1.03.10.0B, Advection of liquids and solids through cracks in the drip shield) and is not considered. Advective seepage onto a waste package could occur due to misplacement of a drip shield leading to breaching of the waste package from localized corrosion. However, the probability of this type of event is very low (4.36×10^{-9} per drip shield (Section 2.3.6.8.4.3.2.4)). Without advective transport, the only remaining mode for fissile material transport is through diffusion.

The minimum fissile mass necessary for criticality external to the waste packages is discussed in *Geochemistry Model Validation Report: External Accumulation Model* (SNL 2007a, Section 8.1.4[a]) where it was concluded that insufficient fissile material can collect over 10,000 years to achieve a critical mass for the seismic or igneous scenarios. These scenarios result in advective flow paths through the waste package that are bounding for the diffusive transport mechanisms. The critical mass limits were evaluated for several waste forms using bounding parameters with regards to optimizing criticality potential (e.g., invert void space and pores within the host rock are represented as being filled with water with fissile material represented in solution and as lumps to minimize resonance absorption within a repeating array). Hence the actual masses that would be necessary to achieve criticality are far greater than what is identified in Table 2.2-14.

The DOE SNF waste forms addressed in *Geochemistry Model Validation Report: External Accumulation Model* (SNL 2007a) (i.e., N Reactor (DOE3), TMI (DOE9), and FFTF (DOE1)) make up approximately 90% of the metric tons of heavy metal in the DOE SNF inventory expected to be disposed of in the repository. Naval SNF and some of the other DOE SNF with high enrichments, such as Shippingport LWBR (DOE5) and Fort St. Vrain (DOE6), are also not expected to increase the probability of an external criticality event due to inherent features and processes, such as the corrosion resistance of the waste form (SNL 2007a, Section 6.9.3[a] and Naval Nuclear Propulsion Program Technical Support Document, Section 2.3.7).

Fort St. Vrain fuels (DOE6) have an integral silicon carbide (SiC) protective layer that not only retains the fission products but also protects the uranium and thorium dicarbide (ThC2) from oxidation and hydrolysis (DOE 2003, p. 48). Comparative analysis has indicated that the Fort St. Vrain fuel has the lowest degradation rate of all DOE SNF and should behave significantly better in terms of fissile material dissolution, transport, and accumulation than the DOE SNF waste forms evaluated in SNL 2007a, Section 6.9.2[a]. A canister loaded with five Fort St. Vrain blocks contains sufficient quantities of ^{233}U to have criticality potential in solution; however, a mechanism to separate the uranium from within the SiC coated fertile particles, and then a mechanism to accumulate in a concentrated fissile mass in a favorable geometry is not credible.

For Shippingport LWBR fuel (DOE5), a number of studies has indicated both air and water oxidation of uranium and thorium oxide fuel pellets ($(Th, U)O_2$) proceed more slowly than in pure uranium oxide (UO_2), and decreases with decreasing UO_2 content in the Th, UO_2 (DOE 2003, p. 33). Tests have shown that the thorium oxide pellets in the Shippingport LWBR fuel have excellent corrosion resistance with an estimated solubility of 10^{-14} mol/L at 25°C and pH>5 (DOE 2003, p. 32). With the less-reactive degradation rate, a mechanism to separate, transport, and accumulate the uranium in a favorable geometry is also not credible.

Naval SNF and DOE fuel groups in Table 2.2-12, DOE2, DOE4, DOE7, and DOE8 representing UZrHx (TRIGA), high enriched uranium oxide (Shippingport PWR), Aluminum based (ATR), and U-Zr/U-Mo alloy (Fermi), have not been analyzed in detail for external fissile mass transport and accumulation as the other waste forms have. However, considering the processes that must occur to allow advective seepage into a DOE or naval SNF canister without substantial drainage to allow degradation of the internal components and waste form, along with the other conservative modeling parameters that have been used to create a process to facilitate fissile material transport to the external environment, and the bounding modeling parameters respective to maximizing criticality potential, these waste forms are not expected to result in an increase in the total probability of criticality which is dominated by the seismic internal degraded probability listed in Table 2.2-8.

Some of the conservative modeling parameters that have been considered for the basis of this conclusion are provided as follows:

- The material degradation and release model (SNL 2007b) uses constant corrosion rates for the SNF. However, laboratory experiments on the surface structure of commercial SNF during dissolution have shown that UO_2 dissolution is accompanied by the formation of a protective layer of secondary phases that retards further corrosion (SNL 2007b, Section 6.6.2). Therefore, the release of uranium from the fuel would be slower than modeled and less would be released.

- In addition, experimental and field data indicate that actinides would be adsorbed on or incorporated into alteration products that form in the waste package (SNL 2007b, Section 6.6.3). This solid solution formation and adsorption would tend to lower actinide concentrations below those predicted by EQ6 and would delay release from the waste package.

- The material degradation and release model (SNL 2007b) assumes the cladding and DOE SNF canister fail immediately, whereas a more likely scenario would be that the failure would take place over many years. This would also delay the release of actinides.

In addition, many conservative assumptions are used to simplify the critical mass calculations presented in Table 2.2-14. For the CSNF and low-enriched DOE fuels analyzed in *Geochemistry Model Validation Report: External Accumulation Model* (SNL 2007a), the conservatisms are appropriate because they are optimized conditions and the results show that a criticality is very unlikely. This modeling approach results in very conservative estimates for criticality evaluations.

Table 2.2-14 shows the ranges of minimum critical mass required to accumulate in the invert as well as the calculated accumulation or mass released from the waste package for the waste forms evaluated for external criticality. The results indicate that under bounding seepage fluxes resulting from a seismic or igneous initiating event, an insufficient amount of fissile material would accumulate in the near-field to pose a criticality concern. Additionally, it can be concluded that, under nominal repository conditions, an insufficient amount of fissile material can accumulate in the near-field location to pose a criticality concern. Therefore, the probability of near-field criticality is insignificant.

2.2.1.4.1.3.4 Potential Far-Field Configurations

The far-field configuration locations for analyses using the disposal criticality analysis methodology include the locations beyond the emplacement drifts. The configurations were considered for both the nominal and initiating event scenarios. The far-field configurations are summarized in descriptions of the criticality FEPs 2.2.14.09.0A, Far-field criticality; 2.2.14.10.0A, Far-field criticality resulting from a seismic event; 2.2.14.11.0A, Far-field criticality resulting from rockfall; and 2.2.14.12.0A, Far-field criticality resulting from an igneous event, and more fully in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008e, Section 6).

Potential accumulation sites for fissile material beneath a degrading waste package in the far-field are within fractures of the host rock and within larger void spaces (lithophysae) distributed throughout the host rock. Lithophysae are hollow, bubble-like structures in the rock composed of concentric shells of finely crystalline alkali feldspar, quartz, and other materials (SNL 2007a, Section 1). The primary mechanisms for accumulation are (1) adsorption and (2) mixing of the actinide-laden source term with resident water, thus changing the chemistry sufficiently for fissile minerals to become insoluble and precipitate (SNL 2007a, Section 1). In order for fissile material to accumulate in the far field, the waste package effluent containing dissolved uranium and plutonium must (1) flow through the invert without interaction with invert materials; (2) enter the fractured tuff, and (3) mix with water that was diverted around the drift that is now in these same fractures or lithophysae. After the effluent and "new" water mixes, uranium and plutonium may precipitate within the fractures and lithophysae.

Like near-field criticality, far-field criticality cannot occur unless the waste package and waste form are degraded. Water infiltration is required to degrade the waste form and waste package internals, and transport fissile material to the far-field location. Criticality cannot occur unless at least the minimum critical mass of a waste form can be accumulated. The probability of an external criticality event is expected to be lower than the probability of an in-package criticality event. This is because, in addition to the events evaluated to calculate the probability of water infiltrating a breached waste package, the probability of the following events must also be considered for far-field external criticality:

- Separation of the fissile materials from the degraded waste form
- Sufficient seepage water to transport fissile materials from the waste package
- Accumulation of sufficient fissile material into a potentially critical configuration in the far-field environment.

As indicated in Section 2.2.1.4.1.3.3, advective flow of water is necessary for transporting fissile materials from the waste package to the far-field in any appreciable quantities to be considered for criticality. Advective seepage through a waste package in the nominal scenario could occur due to misplacement of a drip shield leading to breaching of the waste package from localized corrosion. However, the probability of this type of event is very low (4.36×10^{-9} per drip shield (Section 2.3.6.8.4.3.2.4)).

Without sufficient water to enter the breached waste packages, there is no mechanism to sufficiently degrade the waste package internals and waste form, and transport fissile material into the far-field environment for accumulation and formation of a potentially critical configuration. The minimum fissile mass necessary for criticality external to the waste packages is discussed in *Geochemistry*

Model Validation Report: External Accumulation Model (SNL 2007a, Section 8.1.4[a]), where it was concluded that insufficient fissile material can collect over 10,000 years to achieve a critical mass for the igneous and seismic scenarios. The critical mass limits were evaluated for several waste forms using bounding parameters with regards to optimizing criticality potential, and indicated that the development of a critical mass in the far-field locations for several of the waste forms is not credible (Table 2.2-14).

See Section 2.2.1.4.1.3.3 for a discussion on the DOE waste forms that were not explicitly analyzed and rationale for why they are not expected to change the conclusions regarding far-field criticality based on the waste forms that have been analyzed. Table 2.2-14 shows the ranges of minimum critical mass required to accumulate in the far-field fractures or lithophysae as well as the calculated accumulation or mass released from the waste package for the waste forms evaluated for external criticality. For each of the waste forms evaluated, the results indicate that an insufficient amount of fissile material accumulates to pose a criticality concern. Therefore, the probability of far-field criticality is insignificant.

2.2.1.4.1.4 Summary of Criticality Event Class Screening

The evaluation of the Criticality Event Class has followed the disposal criticality analysis methodology (YMP 2003) that is summarized in Section 2.2.1.4.1.1 and provides the basis by which nuclear criticality is screened from the postclosure performance assessment based on low probability.

The evaluation demonstrates that, as designed, there is an insufficient amount of fissile material in a configuration, an insufficient amount of moderator, and an insufficient loss of neutron absorber material for the contents of a waste package to experience a criticality event. The probabilities for changes in these conditions have been thoroughly evaluated, and as shown in Table 2.2-8, the total probability of criticality is below the proposed 10 CFR 63.342(a) limit of one chance in 10,000 (10^{-4}) of occurring within 10,000 years of disposal. This probability estimate has been developed on a very conservative basis with respect to criticality events and is below the regulatory probability criterion.

2.2.2 Identification of Events with Probabilities Greater Than 1 Chance in 10,000 of Occurring over 10,000 Years

[NUREG-1804, Section 2.2.1.2.2.3: AC 1, AC 2, AC 3, AC 4, AC 5]

Section 2.2.1.2 describes the exclusion of FEPs from the TSPA based on one of three screening criteria: low probability, low consequence (including low impact), or by regulation. This section addresses the identification of event probabilities relevant to the probability screening criterion.

Five potential events were identified in Section 2.2.1.1: early failure, seismic activity initiated events, igneous activity initiated events, criticality initiated events, and human intrusion. Rockfall, previously identified as a separate event, has been included within seismic activity initiated events. Three of these events (seismic activity, igneous activity, and early failure) have been retained for inclusion in the performance assessment conducted to demonstrate compliance with proposed 10 CFR 63.311 based on probability of occurrence. The human intrusion event has been retained for inclusion in the performance assessment conducted to demonstrate compliance with proposed

10 CFR 63.321 consistent with the regulatory requirements of at 10 CFR 63.322. The probability of these four event-related scenario classes is presented in this section. The probability of the criticality event was presented in Section 2.2.1.4.

2.2.2.1 Seismic Activity

[NUREG-1804, Section 2.2.1.2.2.3: AC 1, AC 2, AC 3, AC 4, AC 5]

Seismic hazard for the Yucca Mountain site is assessed probabilistically. Results are provided in terms of the annual probability with which different levels of vibratory ground motion and fault displacement are expected to be exceeded. For some levels of ground motion and fault displacement the annual probabilities of exceedance are greater than 10^{-8} and thus are included in the TSPA (SNL 2008b, Section 6.6.1).

For vibratory ground motion, assessment of hazard for the waste emplacement level involves three steps:

1. A probabilistic seismic hazard analysis (PSHA) to determine the annual probability that vibratory ground motion will be exceeded for a hypothetical reference rock outcrop at Yucca Mountain (CRWMS M&O 1998a; BSC 2004h).

2. Ground motion site-response modeling to account for the effect on ground motion of the site-specific material (i.e., tuff) lying above rock with the conditions defined for the PSHA reference rock outcrop. Site-response modeling and use of its results to determine ground motions for the waste emplacement level is carried out in a manner that preserves the probability of the underlying PSHA results (BSC 2004i).

3. Conditioning of the site-specific results to account for new information on the level of extreme, low-probability ground motion that is consistent with the geologic setting of Yucca Mountain (BSC 2005).

These three steps are also implemented to determine vibratory ground motion used in preclosure design and safety analyses (Section 1.1.5). For preclosure analyses, the PSHA results are conditioned to account for new information on the level of extreme ground motion that is consistent with the geologic setting of Yucca Mountain before they are used to determine site-specific ground motions for the waste emplacement level and for the surface facilities area (BSC 2008).

For fault displacement, assessment of hazard involves a single step. The PSHA determined the annual probability with which different levels of fault displacement are expected to be exceeded for nine representative sites in the vicinity of Yucca Mountain as summarized in Table 2.2-15. These results are used directly in analyses and modeling providing input to TSPA and in preclosure analyses as described in Sections 2.3.4.3 and 1.1.5, respectively.

This section describes the PSHA conducted for the Yucca Mountain site. Section 2.3.4.3.2 describes site-response modeling and use of its results to determine ground motions specifically for the waste emplacement level. Section 2.3.4.3.3 discusses conditioning of the site-specific results to account for new information on the levels of extreme ground motion that are consistent with the geologic setting of Yucca Mountain. Development of ground motions used in preclosure analyses is presented in Section 1.1.5.2.

In describing the PSHA, this section summarizes both the expert elicitation process used and the technical bases underlying the results. An overview of the geologic setting is provided, and the seismicity of the Yucca Mountain region is reviewed. The vibratory ground motion information that formed the basis for expert interpretations and assessments of uncertainty is summarized and the approach used to characterize seismic sources is described in terms of source geometry, earthquake recurrence rate, and maximum earthquake magnitude. Development of ground motion models by the PSHA experts is described and the approach used to characterize fault displacement potential is reviewed. Finally, the variability and uncertainty in interpretations were estimated so they could be included in the seismic hazard results.

2.2.2.1.1 Probability of a Seismic Event

[NUREG-1804, Section 2.2.1.2.2.3: AC 1, AC 2, AC 4]

Seismic hazard is defined as the annual frequency with which a given level of vibratory ground motion or fault displacement is exceeded. To assess seismic hazard at the repository, a PSHA was conducted for the Yucca Mountain site (CRWMS M&O 1998a). To determine inputs for the PSHA, an expert elicitation process was used. Use of an expert elicitation process is described more fully in Section 5.4. The PSHA was performed in three strongly integrated parallel activities that led to the determination of the vibratory ground motion and fault displacement hazard levels for the repository site. The activities performed were (1) evaluation and characterization of seismic sources, including the characterization of potential fault displacement; (2) evaluation and characterization of vibratory ground motion attenuation, including earthquake source, propagation path, and site effects for a defined reference rock condition; and (3) calculations for both fault displacement and vibratory ground motion hazard (CRWMS M&O 1998a, Section 1). The formal PSHA elicitation process that was followed included participation of multiple experts who attended carefully structured workshops and field trips and involved review of available data, the characterization of uncertainties, and documentation of interpretations (CRWMS M&O 1998a, Section 2). Both the preclosure and postclosure performance periods of the repository were addressed in this elicitation. The results of the PSHA form the basis for determinations of seismic inputs at the surface and subsurface for use in analyses supporting design and performance assessment (Sections 1.1.5 and 2.3.4).

Characterization of the epistemic uncertainty and aleatory variability of ground motion, as part of the PSHA, results in ground motion values that increase without bound as lower and lower annual probabilities of exceedance are considered. For annual probabilities of exceedance less than about 10^{-6}, use of these results as input to the ground motion site response model (Section 2.3.4.3) leads to ground motion values for the waste emplacement level that likely exceed those that are consistent with the geologic setting of Yucca Mountain. Additional studies to determine constraints on extreme ground motions, carried out after the PSHA, form the basis for conditioning seismic hazard results for consistency with the geologic setting. (Sections 2.3.4.3.3 and 1.1.5).

2.2.2.1.1.1 Process Used for the PSHA

The PSHA was a multidisciplinary elicitation that supports assessments of long-term repository performance and seismic design criteria development for facility design. The basic elements of the PSHA for vibratory ground motion are listed below (YMP 1997, Section 2.3.1):

- Identify seismic sources that contribute to the vibratory ground motion hazard at Yucca Mountain and characterize their geometry.
- Characterize seismic sources by the recurrence rate of earthquakes of various magnitudes, including the maximum magnitude that can occur.
- Characterize ground motion relationships that specify values for a ground motion parameter as a function of magnitude, source-to-site distance, local site conditions, and, in some cases, seismic source characteristics.
- Integrate the seismic source characterization and ground motion attenuation evaluations, including associated uncertainties, into a seismic hazard curve and associated uncertainty distribution.

The elements of the PSHA for fault displacement hazard analysis follow a similar series of steps:

- Identify sources of fault displacement.
- Characterize the frequency, size, and locations of displacements.
- Characterize the amounts and locations of subsidiary displacements as a function of magnitude and distance.
- Integrate source characterization and distance distribution, including associated uncertainties, into a fault displacement hazard curve and associated uncertainty distribution.

Characterization of uncertainties forms an important element of the PSHA. For the PSHA, a logic tree approach was used to document and incorporate the uncertainties related to different interpretations permitted by the available data (epistemic uncertainty). Random variability in earthquake processes (aleatory uncertainty) was also included in the PSHA calculations (Section 2.2.2.1.5).

Many scientists and engineers contributed to the PSHA. Six teams of earth science experts, with three experts per team, characterized seismic sources in the Yucca Mountain site region (within a distance of about 100 km) and characterized fault displacement potential at nine demonstration points near the repository. Each team was composed of experts in the seismicity, tectonics, and geology of the repository site and region. Ground motion assessments were made by seven individuals who were experts in evaluating the generation and attenuation of earthquake ground motion. The hazard analyses are based on such evaluations that reflect interpretations of scientific hypotheses and models using available data. These interpretations have associated uncertainties related to the ability of data to resolve different hypotheses and models (CRWMS M&O 1998a, Section 1.1).

Interpretations for hazard assessment were coordinated and facilitated through a series of workshops. The workshops provided the expert elicitation methodology, facilitated expert interaction, defined the data needed to perform the evaluations, provided a forum for discussing the range of relevant technical issues and interpretations, and facilitated the presentation and evaluation of available research, as well as previously developed models and interpretations (CRWMS M&O 1998a, Section 1.2).

The strategy for integration or aggregation of the expert evaluations using equal weight was emphasized at the outset of the process. The key procedural components of the process (ranging from the selection of experts to the dissemination of data sets) were designed to allow the equal-weights strategy to be implemented in a defensible manner. A goal of the study was to identify the body and range of uncertainty that would be defined by the larger informed technical community if they provided their evaluations (CRWMS M&O 1998a, Section 2.1).

The PSHA methodology that the DOE used followed the guidance provided by the Senior Seismic Hazard Analysis Committee in a study sponsored by the DOE, NRC, and Electric Power Research Institute (NUREG/CR-6372) (Budnitz et al. 1997). The DOE methodology is documented in *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain* (YMP 1997). This methodology also is generally consistent with NRC-issued guidance on the use of expert elicitation in the high-level radioactive waste program in NUREG-1563 (Kotra et al. 1996) (Section 5.4).

2.2.2.1.1.2 Results from the PSHA

Results of the PSHA consist of ground motion and fault displacement hazard curves. These curves represent the annual probability of exceeding various levels of ground motion or fault displacement at Yucca Mountain. The ground motion results form input to subsequent site response modeling and development of time histories (seismograms) (Section 2.3.4.3.2) that are used in rockfall analyses, dynamic structural response calculations, and seismic consequence abstraction. Each set of time histories provides three-component (two horizontal and one vertical) seismograms for acceleration, velocity, and displacement. Site-response modeling also provides location-specific values of PGV. The fault displacement results from the PSHA are used directly in the abstraction of seismic consequence that provides basic input to the TSPA model abstraction (Section 2.3.4.6).

Ground Motion Results—Based on equally weighted inputs from the six seismic source expert teams and seven ground motion experts, the probabilistic hazard for vibratory ground motion was calculated for a reference rock outcrop. The reference rock outcrop was defined to have, on the basis of available data, the properties of tuff found at a depth of 300 m beneath Yucca Mountain (Section 2.2.2.1.3.2). Ground motion computed at this reference location serves as the basis for site response modeling. The site response model incorporates the effects of the site-specific material properties at the repository to determine seismic inputs at the surface and subsurface for use in analyses supporting design and performance assessment (Section 2.3.4.3.2).

The annual probability of exceeding various levels of ground motion was determined for a random horizontal component and a vertical component of the following ground motion measures:

- Peak ground acceleration (defined as the response spectral acceleration at 100 Hz)
- Response spectral accelerations at frequencies of 0.3, 0.5, 1, 2, 5, 10, and 20 Hz
- PGV.

Examples of hazard curves are shown in Figure 2.2-9 for peak ground acceleration, 10 Hz spectral acceleration, and PGV (BSC 2004i, Section 6.2.2.2). The hazard curves incorporate the assessed variability in earthquake processes; the range of hazard curves (e.g., 5th to 95th percentile) reflects the uncertainty assessed by the experts as incorporated in the PSHA calculations. Mean results for peak ground acceleration; 0.3, 1.0, and 10 Hz spectral acceleration; and PGV are summarized in Table 2.2-16 for the annual exceedance frequencies of 5×10^{-4}, 10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7}.

The ground motion hazard curves represent the integrated hazard derived from the seismic sources, including the effects of variability in earthquake processes and uncertainties in seismic sources and ground motion. The hazard was broken down into its constituent parts in order to understand what types of earthquakes (magnitude and distance combinations) contribute to or dominate the hazard. This breaking down process is termed deaggregation. In addition to highlighting the distribution of magnitudes or distances contributing to the hazard, deaggregation can also include information on how ground motion uncertainty contributes. This is done by computing the parameter epsilon (ε) defined as the difference between the natural logarithm and the mean natural logarithm of the ground motion measure, for a given magnitude and distance, measured in units of standard deviation. If, for a given magnitude and distance, there is a large contribution to ground motion hazard characterized by ε values of 1 to 2, this means that ground motions at 1 to 2 standard deviations above the median are important, not median values. Deaggregation results vary as a function of annual probability of exceedance and the ground motion measure examined (McGuire 1995).

As an example, deaggregation of the mean ground motion hazard for an annual exceedance frequency of 10^{-6} was carried out for two ranges of response spectral acceleration: 5 to 10 Hz and 1 to 2 Hz. For the high frequency range (5 to 10 Hz), ground motions are dominated by earthquakes of smaller than M_w 7.0 occurring at distances less than 15 km from Yucca Mountain (Figure 2.2-10). Contributing events for the low frequency range (1 to 2 Hz) display a bimodal distribution that includes moderate nearby events and M_w 7.0 and larger earthquakes beyond distances of 45 km (Figure 2.2-11). The latter contribution is due mainly to the relatively higher activity rates for the Death Valley Fault and Furnace Creek Fault (BSC 2004h, Section 6.5.4).

The major contributor to the range of ground motion hazard results (e.g., spread between the 5th and 95th percentile) is the ground-motion-expert-specific uncertainty in median ground motion and its variability (within-expert uncertainties). Additional contributions arise from differences between the expert teams (expert-to-expert uncertainties), as well as from the uncertainties expressed by the seismic source logic trees (within-expert uncertainties in seismic source characterization) (CRWMS M&O 1998a, Section 7.4).

Characterization of the epistemic uncertainty and aleatory variability of ground motion, as part of the PSHA, results in ground motion values that increase without bound as lower and lower annual probabilities of exceedance are considered. For annual probabilities of exceedance less than about 10^{-6}, use of these results as input to the ground motion site response model (Sections 2.3.4.3) leads to ground motion values for the waste emplacement level that likely exceed those that are consistent with the geologic setting of Yucca Mountain. Additional studies to determine constraints on extreme ground motions, carried out after the PSHA, form the basis for conditioning seismic hazard results for consistency with the geologic setting (Sections 2.3.4.3.3 and 1.1.5).

Fault Displacement Results—The final fault displacement products of the PSHA are hazard curves showing the annual rate of exceeding particular fault displacement levels at a specific site. The probabilistic fault displacement hazard was calculated for nine demonstration sites located at or near Yucca Mountain (Figure 2.2-12 and Table 2.2-15). Two of the sites, Sites 7 and 8, are evaluated for four hypothetical conditions representative of the features encountered within the Exploratory Studies Facility (ESF): intact rock, a fracture with no measurable displacement, a shear with 10 cm cumulative displacement, and a small fault with 2 m cumulative displacement. The integrated results provide a representation of fault displacement hazard and its uncertainty at the nine locations. Separate results were obtained for each location in the form of summary hazard curves. Figure 2.2-13 shows example results of summary hazard curves for three of the nine demonstration locations (BSC 2004j, Section 4.3.4.2.2).

Potential fault displacement for low annual probabilities of exceedance (e.g., 10^{-6}, 10^{-7}, 10^{-8}), which is considered as part of the assessment of postclosure repository performance, is estimated for all demonstration points examined (Table 2.2-15). At low annual exceedance probabilities, mean displacement on block bounding faults (Bow Ridge Fault, Solitario Canyon Fault), which are outside of the waste emplacement area, exceeds several meters. The assessed displacements on minor faults within the waste emplacement area range from a few centimeters up to about 250 cm (CRWMS M&O 1998a, Section 8.2).

Of the nine demonstration points for which fault displacement hazard was developed in the PSHA, the following are in the immediate vicinity of the repository footprint (SNL 2007j, Section 6.11.3):

- **Site 2**—Solitario Canyon Fault.
- **Site 3**—Drill Hole Wash Fault.
- **Site 4**—Ghost Dance Fault.
- **Site 5**—Sundance Fault.
- **Site 7**—A generic location within the repository, approximately 100 m east of the Solitario Canyon Fault. The ground conditions at the generic location include a hypothetical small fault with 2 m of offset (7a).
- **Site 8**—A generic location within the repository, midway between the Solitario Canyon Fault and the Ghost Dance Fault. The ground conditions at the generic location include a hypothetical small fault with 2 m of offset (8a).

Four named faults intersect the repository emplacement drifts: the Sundance, Pagany Wash, Sever Wash, and Drill Hole Wash Faults (Figure 2.2-12). In addition, a splay of the Ghost Dance Fault also intersects the repository waste emplacement area (SNL 2007j, Table 6-60). The Pagany Wash Fault and the Sever Wash Fault are similar in character to the Drill Hole Wash Fault and are expected to have similar fault displacement hazard results. In evaluating the consequences of fault displacement for TSPA, fault displacement hazard results for the Drill Hole Wash Fault are used for the Pagany Wash Fault and Sever Wash Fault because fault displacement hazard was not explicitly determined for those faults in the PSHA (SNL 2007j, Section 5.1). Results for the Ghost Dance Fault are used for the splay and provide an upper bound for displacement hazard on that splay. Generic locations identified as Site 7 and Site 8 apply throughout the repository. The Solitario Canyon Fault and Ghost Dance Fault, excluding the splay, are adjacent to the repository block, and no waste emplacement drifts intersect these faults.

The fault displacement hazard results display significant uncertainty. Sites with the highest fault displacement hazard show uncertainties comparable to those obtained for ground motion in the PSHA. Sites with low hazard show much higher uncertainties (e.g., a large spread between the 15th and 85th percentile of the hazard distribution (Figure 2.2-13)). This situation largely reflects the data available to characterize fault displacement at the different demonstration locations. For locations for which less data are available, the uncertainties in assessed fault displacement hazard are greater (BSC 2004j, Section 4.3.4.2.2).

2.2.2.1.2 Technical Bases of Probability Estimates
[NUREG-1804, Section 2.2.1.2.2.3: AC 2]

The assessment of earthquake hazards is a function of the seismotectonic framework of the region and vicinity of Yucca Mountain. The seismotectonic framework is characterized by the geologic history of the region, geologic structures that are present, the nature of tectonic processes and stresses that are currently operating, the seismicity that has been observed during the historical period of observation, and the location and rate of activity on regional and local faults. Understanding these processes and their rates of occurrence provides a fundamental basis for assessing seismic hazards by using a probability model.

The PSHA was conducted based on the evaluation of a large set of data pertaining to earthquake sources, fault displacement, and ground motion propagation in the repository region. Tectonic models proposed for the repository area and information from analogue sites in the Basin and Range Province provide the basis to characterize the patterns and amounts of fault displacement. The historical earthquake record, information providing the history of prehistoric earthquakes on nearby Quaternary faults, and information on the attenuation of ground motion are also important components of this data set (BSC 2004j, Section 4.3, pp. 4-29 and 4-30).

The probability estimates obtained from the PSHA have been used to evaluate the seismic-related FEPs that may affect the repository. Specifically, the PSHA provides the underlying basis for the probability or hazard assessments used to assess potential damage to EBS features from seismic-induced rockfall, seismic ground motion, and fault displacement. Specific FEPs assessments with respect to seismic ground motion use values that take into account ground motion site-response and information on the geologic setting of Yucca Mountain that provides constraints on extreme, low-probability ground motions (SNL 2007j, Table 6-2).

The following site characterization activities have produced data for understanding vibratory ground motion and fault displacement hazard at the repository site (BSC 2004j, Section 4.3, p. 4-30):

- Compilation of a historical catalog of earthquakes to support analyses of earthquake recurrence rate and magnitude distribution
- Establishment of a network of seismometers and strong-motion instruments to monitor and characterize contemporary seismicity
- Reconnaissance geologic surveys of known and suspected Quaternary faults within about 100 km of the site to characterize their extent and rates of activity
- Geophysical surveys to identify and characterize the orientation of faults in the subsurface
- Paleoseismic studies of known and suspected Quaternary faults in the immediate vicinity of Yucca Mountain to provide information on past earthquakes, including their number, size, extent, and timing
- Analysis of ground motion data from local earthquakes to evaluate the local attenuation of seismic waves
- Analysis of ground motion data from extensional tectonic regimes to provide information on the regional rate of attenuation.

The probabilistic assessment explicitly incorporates uncertainties in the characterization of seismic sources, fault displacement, and ground motion. The resulting hazard calculations thus represent a sound basis for modeling and analyses to develop ground motion inputs for seismic design and performance assessment by reflecting the interpretations that are supported by data, along with the associated uncertainties in interpretations (BSC 2004j, Section 4.3, p. 4-30).

2.2.2.1.2.1 Geologic Setting

Yucca Mountain reflects a history of volcanism and faulting that have occurred over the past 15 million years. Because the regional tectonic setting continues to undergo deformation, faulting is expected to continue to occur near Yucca Mountain during the postclosure period. A number of alternative tectonic models for Yucca Mountain were proposed to explain observed geologic structures and geophysical data in light of the history of volcanism and fault movement, uplift and subsidence, and lateral extension (Stuckless and Levich 2007, Chapter 4). These models vary from detachment fault models involving extension to lateral-shear pull-apart models. The focus of the assessment of seismic hazards, as expressed in a seismotectonic framework, is the assemblage of contemporary geologic structures and crustal stresses that will give rise to future seismicity. All the models are based on the data and observations regarding the location of structures, the orientation of tectonic stresses, rates of deformation, and observed seismicity. The assessment of seismic sources for the PSHA began with a careful consideration of these data sets and the various tectonic models that were derived from them (BSC 2004j, Section 4.1).

Regional Tectonic Setting—The overall tectonic setting, the Great Basin, generally consists of fault-bounded basins and mountain ranges (including Yucca Mountain) complicated by volcanic activity that has occurred within the past 15 million years. Typically, faults in this setting include normal faults that reflect the extensional deformation caused by plate tectonic interactions at the western margin of the North American continent during the middle and late Cenozoic Era (65 million years ago to the present). The Great Basin is segmented into tectonic domains, structurally bounded blocks of the earth's crust characterized by deformations that distinguish them from adjacent domains. Three regional tectonic domains characterize Yucca Mountain and its surrounding environs: the Walker Lane Domain, which includes the repository site; the Basin and Range Domain, to the northeast; and the Inyo-Mono Domain, to the southwest (Figure 2.2-14) (BSC 2004j, Section 2.2).

Yucca Mountain lies within the Walker Lane Domain, an approximately 100 km wide structural belt along the western side of the Basin and Range Domain. The domain is characterized as an assemblage of crustal blocks separated by discontinuous northwest-striking right-lateral faults and northeast-striking left-lateral faults (BSC 2004j, Section 2.2.1). The geologic setting of Yucca Mountain is characterized structurally by two distinctly different tectonic deformation styles: an earlier compressional orogenic or mountain-building style of regional folding and overthrusting, and a later extensional basin forming style of regional normal and strike-slip faulting (BSC 2004j, Section 2.4).

Contemporary Deformation—Large earthquakes on range-front faults during the past 100 years, such as the Dixie Valley and Fairview Peak earthquakes, indicate that Basin and Range extension is still underway. Epicenter distribution patterns and geodetic strain data indicate that strain is presently concentrated primarily north of Yucca Mountain, in a zone along latitude 37°N (the intermountain seismic belt), in the eastern California shear zone, and in the central Nevada seismic zone. High geodetic extension rates characterize these active areas. Northwest motion of the Sierra Nevada block is accomplished by a combination of east–west extension on north-striking normal faults and by right-lateral motion on northwest-striking strike-slip faults of the Walker Lane and eastern California shear zone (BSC 2004j, Section 2.4.3).

Strain surveys show that the direction of extension in the Great Basin is toward the northwest, the direction of the least compressive stress. The northern Basin and Range appears to be moving by means of crustal extension west-southwest away from continental interior and the southern Great Basin at a rate of 4.9 ±1.3 mm/yr (BSC 2004j, Section 2.4.3). The relatively high strain rate of the northern Basin and Range is at least partly accommodated by the central Nevada seismic zone.

In the Yucca Mountain vicinity, a network of continuously recording Global Positioning System stations has been established, starting in 1999. Data from this network have been interpreted to show right-lateral strain accumulation with a rate on the order of 1 millimeter per year (Wernike et al. 2004; Hill and Blewitt 2006). Such a rate is one or more orders of magnitude higher than the rates determined from geologic evidence for Quaternary fault slip rates at the site (Keefer et al. 2004, Chapter 5), and may represent a short-term variation in the rate of deformation. In evaluating the rate of earthquake occurrence for seismic sources during the PSHA, the experts gave more weight to evidence of long-term average rates over tens to hundreds of thousands of years than to short-term rates over several years to decades.

Regional and Local Faults—The structural geology of Yucca Mountain and vicinity is dominated by a series of north-striking normal faults, along which 8 to 12 million year old (Tertiary) volcanic rocks were tilted eastward and displaced hundreds of meters, chiefly to the west (Figure 2.2-15). Movement occurred primarily during a period of extensional deformation in middle- to late-Miocene time but has continued at a low level into the Quaternary period (the last two million years up to the present day). These normal faults divide the site area into several blocks, each of which is further deformed by intra-block faults (BSC 2004j, Sections 3.5.1 and 3.5.9).

Block-bounding faults within the repository site area are spaced 1 to 5 km apart and include, from east to west, the Paintbrush Canyon, Bow Ridge, Solitario Canyon–Iron Ridge, Fatigue Wash, and Windy Wash faults (Figure 2.2-16) (BSC 2004j, Section 3.5.3). Fault scarps commonly dip from 50° to 80° to the west. Displacements are mainly dip-slip (direction of slip down the fault plane), down-to-the-west, with subordinate strike-slip or oblique-slip components of movement exhibited along some faults. Numerous intrablock faults at the repository occur within the individual structural blocks, representing local adjustments in response to stress created, for the most part, by the displacements that took place along block boundaries (BSC 2004j, Section 3.5.3).

Several of the block-bounding faults show evidence of Quaternary displacements that influenced depositional patterns of surficial materials on hill slopes and on adjacent valley or basin floors. Quaternary displacements also produced visible scarps in surficial deposits along some fault traces. However, low rates of offset and long recurrence intervals between successive faulting events on faults in the site area during Quaternary time have resulted in subtle landforms (BSC 2004j, Section 3.2.2.1, p. 3-4).

2.2.2.1.2.2 Seismicity of the Yucca Mountain Region

Seismic hazard evaluations rely on a description of the temporal and spatial distribution of earthquakes, their magnitudes and other source parameters, their associations with active faults, and how they relate to the seismotectonic processes of the region. The temporal and spatial occurrence of earthquakes for a given region is evaluated from two sources: historical (instrumental records and reported effects) and prehistoric (paleoseismic) data.

In preparation for the PSHA, a catalog of historical earthquakes was compiled for the region within 300 km of Yucca Mountain. The resulting combined catalog contains 271,223 earthquakes occurring from 1868 to 1996. Earthquakes with Richter magnitudes down to approximately 1 were recorded in the more recent periods as the sensitivity of local and regional seismic networks was increased. Figure 2.2-17a shows events in the catalog with magnitude greater than moment magnitude (M_w) 3.5. Figure 2.2-17b shows events with moment magnitude (M_w) greater than 6.0. The accuracy of information in the historical catalog is affected by several variables (e.g., accuracy of historical accounts, detection capability, instrumental precision), especially the variability in seismic network coverage as a function of time. The spatial distribution of seismicity in the 300 km catalog depends both on the density of population and the density of seismographic network coverage in a particular region over time and is an artifact of the more thoroughly represented aftershock sequences of the modern period. Catalog completeness for the region within 100 km of Yucca Mountain was assessed as part of the PSHA (BSC 2004j, Section 4.3.1.2).

Since the Yucca Mountain catalog was compiled from several source catalogs, each using a variety of different magnitude scales that also changed with time, a uniform magnitude scale was required to compute the earthquake recurrence for the region. In addition, it was necessary to assign magnitudes to historical earthquakes that occurred prior to calibrated seismographic instrumentation. For use in the PSHA, a moment magnitude (M_w) was determined for each event based on the available data (CRWMS M&O 1998a, Appendix G). While uncertainty in magnitude conversion was not explicitly addressed, the seismic source characterization experts qualitatively considered such uncertainties in assessing the uncertainty in seismic source recurrence relationships. Underground nuclear explosions at the Nevada Test Site and their induced earthquake aftershocks, and reservoir-induced seismicity events at Lake Mead, were identified in the earthquake catalog. Underground nuclear explosions and related aftershocks, which appear as the prominent clusters of epicenters to the north and east of Yucca Mountain, were excluded for purposes of calculating seismicity recurrence rates for the seismic hazard analysis (BSC 2004j, Section 4.3.1.2). Earthquake occurrence is assumed to be a Poisson process (BSC 2004h, Section 6.4.2).

The larger earthquakes documented in the historical catalog occurred 100 to 300 km to the northwest, west, southwest, and south of Yucca Mountain (Figure 2.2-17b). Three events of greater than M_w 5.5 are located within 100 km of Yucca Mountain (Figure 2.2-18). The largest event is the 1916 M_w 6.1 earthquake that occurred in Death Valley. These events also include the 1992 M_w 5.6 earthquake that occurred near Little Skull Mountain, about 15 km southeast of Yucca Mountain, and an event in 1910 about 85 km to the northwest.

Various analyses have shown that earthquakes in the southern Great Basin occur predominantly between depths of 2 and 12 km. Focal mechanisms of recent earthquakes within the southern Great Basin indicate that right-lateral slip on north-trending faults is the predominant mode of stress release near the site. Focal mechanisms of earthquakes within about 100 km of Yucca Mountain for the period 1971 through 1992 indicate roughly equal proportions of strike-slip and normal faulting. Oblique-slip faulting is also observed (BSC 2004j, Section 4.3.1.4.2).

Seismicity in the Vicinity of Yucca Mountain—While the southern portion of the Nevada Test Site, southeast of Yucca Mountain, is one of the more seismically active regions in the southern Great Basin based on contemporary seismicity, the area immediately around Yucca Mountain (within 10 km) has relatively little seismicity (Figure 2.2-19). Studies, including an experiment in high-resolution monitoring of seismicity at the site, have shown that the Yucca Mountain zone of quiescence is a real feature of the contemporary seismicity and not an artifact of network design or detection capability. Seismicity in the vicinity of Yucca Mountain from October 1, 1995, to September 30, 2002, is shown in Figure 2.2-19 (BSC 2004j, Section 4.3.1.5). The large number of very small earthquakes detected near Little Skull Mountain (to the southeast of Yucca Mountain) is the result of improved seismic monitoring capabilities instituted after 1995 and is mainly due to aftershocks of the June 1992 Little Skull Mountain earthquake.

While the immediate Yucca Mountain area has been quiescent during the historical period, paleoseismic evidence indicates active Quaternary faults exist near the site. Paleoseismic events exhibit long times between events; thus, little or no microseismicity may occur on the faults during the historical period of observation. Many faults in the Great Basin with paleoseismic evidence for prehistoric surface-rupture earthquakes have little or no associated historical seismicity (BSC 2004j, Section 4.3.1.5).

Seismicity to the east and southeast of Yucca Mountain is spatially associated with the Rock Valley, Mine Mountain, and Cane Spring Fault zones (Figure 2.2-20). This activity forms a wide, northeast-trending zone that includes the 1973 Ranger Mountain sequence, the 1992 Little Skull Mountain sequence, the 1993 Rock Valley sequence, the 1999 Frenchman Flat sequence, and other earthquake clusters (Figure 2.2-18). The main shocks from the Little Skull Mountain and Frenchman Flat sequences, near the ends of the seismicity zone, exhibited normal faulting on northeasterly striking planes. The Rock Valley sequence in the middle of the zone exhibited strike-slip faulting. Some seismicity in the Yucca Mountain area is also spatially associated with the southern boundary of a caldera located to the north of Yucca Mountain (BSC 2004j, Section 4.3.1.5).

Paleoseismic Data—The prehistoric earthquake history of the repository site spans at least the past several hundred thousand years and is particularly important for probabilistic seismic hazard analyses because it extends the record for larger magnitude events (magnitude greater than about 6). Paleoseismic studies are the basis for identifying the occurrence of large-magnitude surface-rupturing earthquakes and evaluating their size, age, and occurrence rate. Regional investigations were conducted to identify faults within 100 km of the Yucca Mountain area that have evidence of Quaternary displacements (Figure 2.2-20) (BSC 2004j, Section 4.3.2).

Displaced or deformed sedimentary deposits record late Quaternary faulting along nine local faults in the Yucca Mountain area (Keefer et al. 2004). These faults include, from west to east, the Northern Crater Flat, Southern Crater Flat, Windy Wash, Fatigue Wash, Solitario Canyon, Iron Ridge, Stagecoach Road, Bow Ridge, and Paintbrush Canyon faults (Figure 2.2-20b). Paleoseismic data for these faults provide the basis for interpretations made as part of the PSHA (BSC 2004j, Section 4.3.2). Geologic studies of the local faults in the Yucca Mountain area resulted in data and interpretations of key paleoseismic characteristics that define the size and rate of occurrence of prehistoric earthquakes on these faults. These characteristics include fault slip rate, displacements associated with individual paleoseismic events, lengths of rupture, and recurrence intervals between individual paleoseismic events.

Fault slip rate is the time-averaged rate of displacement on a fault in millimeters per year. Fault slip rates were computed at each trench site from measurements of the observed net displacement of one or more dated units. Minimum, maximum, and preferred slip rates were calculated at each site, with the range of values reflecting uncertainties in both age control and displacement measurements. Meaningful slip rates should span at least several seismic cycles, encompassing multiple displacement events. This is particularly important for long recurrence, low slip-rate faults such as those observed at Yucca Mountain. The spatial distribution of fault slip-rate measurements for local faults at Yucca Mountain is determined by the distribution of trench sites with suitable paleoseismic data. One to four slip-rate determinations were computed for nine of the Quaternary faults at Yucca Mountain, as well as the nearby Bare Mountain and Rock Valley Faults. Estimates of slip rates for faults at Yucca Mountain vary from 0.001 to 0.07 mm/yr (BSC 2004j, Section 4.3.2.1). Even given the uncertainties in slip-rate estimation, the slip rates at Yucca Mountain are low to very low relative to slip rates on other faults in the Basin and Range Province.

The surface displacement that occurred in individual paleoseismic earthquakes (per-event displacement) is an important parameter to estimate the magnitude of prehistoric earthquakes. The most precise per-event displacements were estimated directly from trench log data. Multiple measurements of per-event displacement are available for local faults at Yucca Mountain. Measurement uncertainties are included in the range of displacements reported. The resolution of per-event displacement measurements generally decreases with increasing age because of the propagation of measurement error for successively older displacements in an event sequence (BSC 2004j, Section 4.3.2.2).

Per-event displacements for local block-bounding faults vary from near 0 to 257 cm. Displacements per event are larger (80 cm to less than 362 cm) for the more distant Rock Valley and Bare Mountain faults relative to the block-bounding faults at Yucca Mountain. Available estimates of single-event displacements for regional faults are in the general range of those for local faults, with the exception of displacements of 240 to 470 cm on the Death Valley–Furnace Creek Fault system (BSC 2004j, Section 4.3.2.2).

Surface-rupture length is an important parameter used to define the magnitudes of prehistoric earthquakes. Rupture lengths of individual local faults and regional faults in the Yucca Mountain area were interpreted (Section 2.2.2.1.3.1). Individual local fault-rupture lengths range from 1 to about 25 km. Fault lengths in the region surrounding the site range from several kilometers to more than 300 km for the Death Valley–Furnace Creek–Fish Lake Fault system (BSC 2004j, Section 4.3.2.3).

Recurrence interval is defined as the time interval between successive surface-rupture earthquakes. At least one and commonly two or more recurrence interval estimates are made along individual faults at Yucca Mountain. Average recurrence intervals of individual faults range from 5,000 to 270,000 years. The long recurrence intervals likely result from relatively small numbers of observed displacements in middle Pleistocene deposits and are consistent with the estimated low fault slip rates (BSC 2004j, Section 4.3.2.4).

2.2.2.1.2.3 Vibratory Ground Motion Information

In the seismic hazard analysis for the repository site, assessments are made of the size and recurrence rate of earthquakes that seismic sources might generate and the propagation of earthquake energy from the source to the repository site. The level of ground motion that will be experienced at the site for any given earthquake location and magnitude must be assessed and described by ground motion prediction relationships, also called attenuation relationships. Ground motion attenuation relationships describe the dependence of the amplitude of the ground motions as a function of earthquake magnitude, distance from the earthquake, and local site conditions.

To the extent possible, the vibratory ground motions adopted for the seismic design of the repository (discussed in Section 1.1.5.2) and analysis of its postclosure performance (discussed in Section 2.3.4.3.2) should incorporate the effects of the seismic sources, propagation path, and local site geology specific to the Yucca Mountain region and site. Ideally, recorded ground motion from earthquakes in the Yucca Mountain region or Basin and Range Province would be used directly to develop attenuation relationships for application at the repository. However, because no large earthquakes have occurred in the region during the period of strong-motion instrumentation, such data are insufficient to constrain site-specific empirical models (BSC 2004j, Section 4.3.3). Rather, the few data recorded in the Yucca Mountain region and the geophysical and seismological properties derived for the region form the basis for adjusting ground motion attenuation relationships from other areas and for numerical modeling of site-specific ground motions to apply at the repository site (BSC 2004j, Section 4.3.3).

Characterizing ground motion at the repository using existing attenuation relationships involves resolving whether, and to what extent the available relationships for the western United States are applicable to the Basin and Range Province, in general, and to Yucca Mountain, in particular. The seismological questions include whether differences in the factors that influence ground motion in the Yucca Mountain region and in the western United States would lead to significant differences in ground motion estimates for the two regions. These factors include seismic source properties, regional crustal properties, and shallow geologic site properties at the repository. Generally, comparisons must be made between Yucca Mountain factors and average factors inherent in the strong-motion database used to develop relationships for the western United States (Section 2.2.2.1.3.2). To address these issues, six ground motion studies were carried out as part of site characterization activities (BSC 2004j, Section 4.3.3):

- The first study was an empirical analysis of worldwide ground motion data from extensional regimes.
- The second study comprised numerical modeling of selected scenario earthquakes near Yucca Mountain in which ground motions were estimated using seismological models of the source, path, and site effects. The numerical modeling allowed the region-specific crustal structure and site-specific rock properties to be incorporated in the ground motion estimates.
- The third study used weak motion recordings to characterize the near-surface seismic wave attenuation at Yucca Mountain.
- The fourth study examined earthquake stress drops in extensional regimes to compare them to those for earthquakes used to develop western United States ground-motion attenuation relationships. Stress drop is a factor in determining the level of high-frequency ground motion.
- The fifth study investigated the possible constraint that precariously balanced rocks can provide on the levels of ground motion that have occurred in the past.
- The sixth study is the ground motion characterization performed as part of the PSHA project and is the most comprehensive of the six. Incorporating results from the other five studies, this study resulted in ground motion attenuation relationships specific to Yucca Mountain (BSC 2004j, Section 4.3.4.1.3).

Study 1: Attenuation of Strong Motion in Extensional Regimes—Yucca Mountain is situated in an extensional tectonic regime. Thus, to develop a ground motion attenuation relationship appropriate for the site region, data from extensional regimes, such as the Basin and Range Province, were compiled and analyzed. Because the number of events in the Basin and Range

Province is limited, the database includes ground motion recorded in extensional regimes worldwide (BSC 2004j, Section 4.3.3.2).

Several representative attenuation relationships based on data from the western United States were compared to the extensional data (Spudich, Fletcher et al. 1996). The mean residual, or bias, was computed for each attenuation relationship and indicates whether that relationship systematically underpredicts or overpredicts the extensional strong-motion data. In general, the computed residuals indicate that the standard western United States attenuation relationships available in the mid 1990s overpredict ground motion from extensional regimes by about 15% to 35% on average (BSC 2004j, Section 4.3.3.2).

Another element of this study consisted of developing an attenuation relationship specifically for extensional regimes (SEA96) (Spudich, Fletcher et al. 1997). Comparisons of median predictions from this relationship with those from several western United States attenuation relationships illustrate their differences. In general, at short to moderate periods, the predictions of the SEA96 relationship are less than, or lie at the lower limit of, the values predicted by other western United States relationships. At long periods, the SEA96 relationship is similar to the western United States relationships. Notably, however, the SEA96 relationship has a much larger standard deviation at long periods than is usual for the western United States relationships (BSC 2004j, Section 4.3.3.2). The SEA96 relationship was one attenuation relationship considered by the ground motion experts as part of the PSHA (BSC 2004h, Table 8).

The attenuation relationship for extensional tectonic regimes was updated using a larger data set and minor errors in the data set used for the earlier analysis were corrected (Spudich, Joyner et al. 1999). At short distances, 5 to 30 km, ground motions predicted by the new relationship (SEA99) are up to 20% higher than those predicted by the SEA96 relationship, while at longer periods (1.0 to 2.0 seconds) and larger distances (40 to 100 km) they are about 20% lower (Spudich, Joyner et al. 1999, p. 1156). When compared to ground motions determined from the relationship of Boore et al. (1994), results average about 20% lower, except for short distances at periods around 1.0 second. For this combination, the ground motions from SEA99 exceed those determined from the Boore relationship (Boore et al. 1994) by up to 10% (BSC 2004j, Section 4.3.3.2).

Spudich, Joyner et al. (1999) also note that for rock sites the attenuation relationship overestimates the data by about 20%. Pankow and Pechmann (2004) revised the Spudich, Joyner et al. (1999) attenuation relationship to correct for this bias.

Study 2: Ground Motion from Yucca Mountain Scenario Earthquakes—Due to the lack of near-fault strong-motion data from earthquakes in the Basin and Range Province (including the Yucca Mountain region), a study was carried out to estimate vibratory ground motion for several earthquake scenarios potentially affecting the repository. The six experts who conducted the study used established numerical modeling methods to simulate ground motion that was appropriate to the specific conditions at the repository site. As part of the modeling exercise, median ground motion and its variability were estimated for each earthquake scenario (BSC 2004j, Section 4.3.3.3).

Six earthquake scenarios were evaluated based on two criteria: (1) the postulated sources are likely to have generated significant earthquakes in the past; and (2) they are considered likely to produce ground motion that would impact seismic hazard estimates at the repository. The six scenarios include four normal faulting events (M_w 6.3 to 6.6) at source-to-site distances of 1 to 15.5 km and two strike-slip faulting events (M_w 6.7 and 7.0) at source-to-site distances of 25 and 50 km, respectively (BSC 2004j, Section 4.3.3.3). More distant, but larger magnitude earthquakes have a significant contribution to ground motion hazard at Yucca Mountain for response spectral frequencies in the 1 to 2 Hz range for mean annual probabilities of exceedance greater than about 1.0×10^{-6} (BSC 2004i, Section 6.2.2.4).

Six modeling approaches were included in the study. The methods vary significantly in their treatment of wave propagation, site response, and overall level of complexity, but all the methods accommodate the essential aspects of seismic energy being generated from a finite source and propagated along a path to a site at the earth's surface. Differences in resulting predictions capture an important component of the ground motion uncertainty in these scenario earthquakes that can be applied to the variability of other simulations (BSC 2004j, Section 4.3.3.3).

The study included a validation phase in which the six participants incorporated various Yucca Mountain source, path, and site parameters to calibrate their models to best fit ground motion from five sites that recorded the 1992 Little Skull Mountain earthquake. Five of the six methods had also been previously calibrated against recordings from other earthquakes (BSC 2004j, Section 4.3.3.3; Schneider et al. 1996, Appendix B).

The models produced ground motion estimates that were comparatively unbiased for periods of less than 1 second, indicating that they are applicable to estimating ground motion in the Basin and Range Province. However, the bias for periods greater than 1 second indicates that the numerical simulation models do not work well for the 1992 Little Skull Mountain earthquake at long periods (BSC 2004j, Section 4.3.3.3).

Using the Little Skull Mountain–calibrated models, the six teams computed motions for the six faulting scenarios. Five of the teams whose models were numerical simulations (i.e., all except an empirical underground nuclear explosion model) ran multiple realizations of the source process and computed a mean spectrum for each scenario. Ground motion computed for the normal faulting scenario events at close distances (Bow Ridge, Solitario Canyon, and Paintbrush Canyon faults) is large: 34-Hz spectral accelerations range from 0.5 to 1.0 g at distances of 1 to 3 km (BSC 2004j, Section 4.3.3.3).

The model simulations were compared with several western United States empirical attenuation relationships. The simulated median ground motion for the four normal faulting scenario events exceed the western United States predictions by about 60% at distances less than 5 km and by about 20% at 15 km. The differences are largest at high frequencies, attributable primarily to low site attenuation in the shallow rock at Yucca Mountain and to larger crustal amplification for the Basin and Range Province. At long periods, the difference is attributed to the larger crustal amplification and directivity effects (stronger ground motion in the direction of rupture propagation than in other directions from the earthquake source) (BSC 2004j, Section 4.3.3.3).

For the more distant strike-slip faulting earthquakes, the simulated median ground motion is greater than the western United States attenuation predictions by about 30% at a distance of 25 km at high frequencies. This increase is similarly attributed to low site attenuation and larger crustal amplification. At 50 km, the simulated longer period ground motion is consistent with western United States empirical attenuation predictions because the effect of local site attenuation is not as significant (BSC 2004j, Section 4.3.3.3).

The simulated higher ground motion at high frequencies is consistent with records from the 1992 Little Skull Mountain earthquake. The high-frequency ground motion from this event was significantly larger than that predicted by western United States empirical attenuation relationships. The variability of the simulated motion is also greater than that computed for western United States empirical attenuation relationships. The standard error is about 0.15 natural log units larger than that found for empirical attenuation relationships (BSC 2004j, Section 4.3.3.3).

Numerical simulations using several of the methods from this study were subsequently used during the PSHA to provide part of the ground motion database considered by the ground motion experts (CRWMS M&O 1998a, Section 5.4).

Study 3: Site Attenuation—Recordings of regional earthquakes at Yucca Mountain (Su et al. 1996) were used to evaluate the near-surface attenuation. Results indicated that site attenuation at Yucca Mountain is lower than for typical California soft rock. Therefore, at low levels of shaking, damping from the tuff is less than that for California soft-rock conditions. This difference in damping leads to larger high-frequency ground motion on the tuff as compared to that on California soft rock, assuming that all other parameters are the same. The results were used to provide a site attenuation value for the Yucca Mountain PSHA (BSC 2004j, Section 4.3.3.1).

Site attenuation was also measured (Biasi and Smith 1998, pp. 2 to 3) from very small earthquakes in the Yucca Mountain vicinity using a different approach than Su et al. (1996). Results from about 250 earthquakes indicate a significantly larger site attenuation than obtained by Su et al. (1996). To explain the difference, Biasi and Smith suggest that the earthquake source model used in the Su et al. study underestimates the average radiated high-frequency energy (BSC 2004j, Section 4.3.3.1). The larger site attenuation would imply lower ground motion, at least at high frequency relative to those determined in the PSHA.

Study 4: Earthquake Stress Drop—Stress drop is the difference in stress across the fault before and after an earthquake, and it affects high-frequency ground motion. If stress drops in the Yucca Mountain region were greater than the typical value for western United States earthquakes, then larger high-frequency motions would be expected at Yucca Mountain relative to motions determined from western United States empirical attenuation relationships. An evaluation of stress drops for earthquakes in extensional regimes was performed to provide data for assessing this potential effect and to support the ground motion characterization effort in the PSHA project (BSC 2004j, Section 4.3.3.1).

The analysis used a data set composed of earthquake records from extensional tectonic regimes, including both normal and strike-slip events that comprised 210 horizontal components from 140 sites in 24 earthquakes, a magnitude range of M_w 5.1 to 6.9, and distances from 0 to 102 km. The data were fit to a standard earthquake source model, and a two-step inversion process was adopted to decouple the inversions for site attenuation and stress drop. Stress drops computed for each earthquake were weighted to yield a median value for each mechanism (BSC 2004j, Section 4.3.3.1).

The median stress drop for normal-faulting earthquakes was about 4.5 MPa, and the value for strike-slip earthquakes (in extensional regimes) was about 5.5 MPa. In comparison, stress drops for western United States earthquakes are about 7 to 10 MPa (Atkinson 1995, p. 1341). These differences in stress drop contribute to lower high-frequency motions in extensional regimes compared to transpressional regimes, such as coastal California. This information was considered in the ground motion characterization component of the PSHA for Yucca Mountain (BSC 2004j, Section 4.3.3.1).

Study 5: Implications for Vibratory Ground Motion from Studies of Precariously Balanced Rocks at Yucca Mountain—The existence of precariously balanced rocks in the Yucca Mountain region may place some constraints on the level of vibratory ground motion experienced at the site over the past several tens of thousands of years. Precariously balanced rocks provide evidence that past levels of strong vibratory ground motion were insufficient to topple them. In areas where strong ground motion is known to have occurred historically, precariously balanced rocks are not observed. For example, based on reconnaissance field surveys in southern California, it was concluded (Brune 1996, p. 43) that no precarious rocks are found within 15 km of zones of high-energy release from historical large earthquakes. Laboratory physical modeling, numerical modeling, and field tests provide confidence that rough estimates of the accelerations required to topple precarious rocks can be made without extensive controlled testing. Brune and Whitney (2000, p. 18) noted that numerous precarious rocks exist along Solitario Canyon and argued that accelerations at Yucca Mountain have not exceeded about 0.3 g at the surface during the past 75,000 to 80,000 years. Vibratory ground motion at the depth of waste emplacement would be less than that at the earth’s surface (BSC 2004j, Section 4.3.3.4).

Precarious rocks have also been used to test ground motion attenuation relationships. In contrast to observations in the vicinity of strike-slip faults, precarious and semiprecarious rocks are found near the fault trace on the footwall side of normal faults in Nevada and California (Brune 2000, p. 1107). Comparison of estimated toppling accelerations with accelerations predicted by a ground motion attenuation relationship that is based largely on data for strike-slip earthquakes suggests that the attenuation relationship may overestimate accelerations on the footwall of normal faults at near distances. This result is consistent with results from dynamic foam rubber models of strike-slip and normal faulting earthquakes. That is, the models indicate that ground motion near the fault trace is less for normal faulting earthquakes than for strike-slip earthquakes. The implication of this observation is that seismic hazard estimates using ground motion attenuation curves based largely on data from strike-slip earthquakes may result in the overestimation of values of hazard for sites such as Yucca Mountain, where normal faulting predominates (BSC 2004j, Section 4.3.3.4).

In addition to the studies carried out specifically to evaluate ground motion issues at Yucca Mountain, in the PSHA the ground motion experts also considered empirical attenuation relationships developed to characterize ground motions in the western United States (e.g., Abrahamson and Silva 1997; Boore et al. 1997; Campbell 1997; Sadigh et al. 1997; Sabetta and Pugliese 1996; Joyner and Boore 1988; McGarr 1984). These relationships are based largely on data from earthquakes in California and, thus, reflect the source, path, and site conditions of that region. For use in the PSHA, the experts developed conversion factors to transform the existing attenuation relationships into ones applicable to the Yucca Mountain site.

2.2.2.1.2.4 Fault Displacement

In evaluating the potential for fault displacement at the repository, two types of displacement are considered: principal and distributed. Principal faulting is the faulting along the main plane (or planes) of crustal weakness that is responsible for the primary release of seismic energy during an earthquake. Where the principal fault rupture extends to the surface, it may be represented by displacement along a single narrow trace or over a zone that is a few meters wide. Distributed faulting is rupture that occurs on other faults in the vicinity of the principal rupture in response to the principal displacement. It is expected that distributed faulting will be discontinuous in nature and occur over a zone that may extend outward several tens of meters to many kilometers from the principal rupture. A fault that can produce principal rupture may also undergo distributed faulting in response to principal rupture on other faults (BSC 2004j, Section 4.3.4.1.2).

To evaluate the characteristics of principal and distributed faulting for Yucca Mountain, information on 100 historical earthquakes that occurred in the extensional cordillera of the western United States was compiled and evaluated. The evaluation focused on the amounts and patterns of both principal and distributed fault displacements, the minimum magnitude at which an earthquake may produce surface faulting, and the maximum magnitude at which an earthquake does not displace the surface. The evaluation revealed a general correlation of the extent and amplitude of historical surface displacements with earthquake size, seismotectonic setting, hypocentral depth, fault geometry, and style of slip (BSC 2004j, Section 4.3.1.2).

2.2.2.1.3 Adequacy of Probability Model Support
[NUREG-1804, Section 2.2.1.2.2.3: AC 3]

Models comprising input to the PSHA were determined using a formal expert elicitation process (Section 5.4.2). The PSHA methodology is documented in *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain* (YMP 1997). This methodology is consistent with guidance provided by the Senior Seismic Hazard Analysis Committee (Budnitz et al. 1997). The expert elicitation also was conducted in a manner that was generally consistent with NUREG-1563 (Kotra et al. 1996), which was issued after the PSHA had been initiated. The probability model developed for the PSHA is based on extensive geologic, geophysical, and seismological data from the vicinity of Yucca Mountain and the surrounding region (as described in Section 2.2.2.1.2). These data were used to characterize the geologic setting of the site and are also used as the basis for assessments of other potential disruptive events and models described in Section 2.2.1 (e.g., the igneous activity scenario class). In addition, data from reasonably analogous systems or regions were used for assessments that included the evaluation of appropriate attenuation relationships to characterize ground motion (CRWMS M&O 1998a, Section 5.4.1) and the frequency at which earthquakes of various magnitudes rupture the ground surface for the fault displacement analysis (CRWMS M&O 1998a, Section 4.2.4.2).

The essential elements of the seismic source characterization, ground motion attenuation evaluation, and fault displacement characterization are summarized below.

2.2.2.1.3.1 Seismic Source Characterization

As used in the PSHA, a seismic source is defined as a region (or volume) of the earth's crust that has relatively uniform seismicity characteristics, is distinct from those of neighboring sources, and can be used in approximating the locations of future earthquakes. The seismic source characterization expert teams identified two main types of seismic sources: fault sources and areal source zones. For both source types, the geometry of the source, its maximum earthquake magnitude, and the rate of earthquake occurrence were assessed. For each fault source, the probability of activity, style of faulting, and fault interactions, if any, were also assessed. The probabilistic assessment explicitly incorporates uncertainties in the characterization of seismic sources.

Source Geometry—Fault sources are used to represent the occurrence of earthquakes along a known or suspected fault. Faults considered in the PSHA are shown in Figure 2.2-20. Uncertainty in the definition of fault sources is expressed by considering alternative rupture lengths, alternative fault dips, and possible linkages with other faults. In addition, an evaluation is made of the probability that a particular fault is active and capable of generating moderate-to-large earthquakes (BSC 2004j, Section 4.3.4.1.1). For consideration in the PSHA, a number of rupture scenarios were developed. These scenarios include combinations of faults and fault segments that could, based on the available paleoseismic data, rupture synchronously during individual earthquakes (BSC 2004j, Section 4.3.2.3).

Two types of fault sources were included in the PSHA: regional faults and local faults. Regional faults were defined by most teams as Quaternary faults within 100 km of Yucca Mountain but outside the local vicinity of the site that were judged to be capable of generating earthquakes of M_w 5 and larger. Local faults were defined as being located within about 15 km of Yucca Mountain. The specific faults that required detailed characterization were determined based on factors including fault length and location relative to Yucca Mountain, displacement of Quaternary deposits, direct relation with seismicity, structural relation to other Quaternary faults, orientation within the contemporary tectonic stress regime, and considerations of alternative tectonic models. Faults that had short lengths or no significant Quaternary displacement (shown in Figure 2.2-20b) were considered but judged not relevant to the hazard analysis (BSC 2004j, Section 4.3.4.1.1). The local faults included in the PSHA are listed in Table 2.2-17.

The number of regional faults explicitly included by the expert teams in their interpretations ranged from 11 to as many as 36. This reflected, in part, the judgments of the teams regarding the activity of various faults, as well as the decision by some teams to include potentially active faults (e.g., faults having a probability of less than one of being active). Other teams included such faults as part of their background source zones. To characterize local faults, the expert teams employed varying behavioral and structural models that represent the range of possible rupture patterns and fault interactions. Models of the simultaneous rupture of multiple faults were included in all of the expert assessments (BSC 2004j, Section 4.3.4.1.1).

Areal source zones represent regions of distributed seismicity that are not associated with specific known faults. The events are considered to be occurring on unidentified faults or structures whose areal extents are best characterized by zones. Uncertainty in defining areal zones was typically expressed by defining alternative zonations of the region surrounding the repository site. For example, one team interpreted alternative areal source zone configurations that differed according to whether the Walker Lane was treated as a separate zone or not (Figure 2.2-14). For each source zone, the expert teams characterized the zone's maximum magnitude, its rate of earthquake occurrence, and the magnitude distribution of those earthquakes. Uncertainties in these parameters were also quantified (BSC 2004j, Section 4.3.4.1.1).

Areal source zones were defined by all teams to account for background earthquakes that occur on buried faults or other faults not explicitly included in their characterizations. Seismicity related to volcanic processes (specifically to basaltic volcanoes and dike injection) was considered by all six expert teams but explicitly characterized as distinct source zones by only two expert teams. Volcanic-related earthquakes were not modeled as a separate seismic source by the other four teams because the low magnitude and frequency of volcanic-related seismicity was bounded by earthquakes in the areal zones (BSC 2004j, Section 4.3.4.1.1).

Maximum Earthquake Magnitude and Recurrence—For each seismic source considered by an expert team, the team determined the maximum earthquake magnitude (M_{max}) to represent the largest earthquake that the source is capable of generating. Two basic approaches were used to assess maximum magnitude. The primary approach, which was used for faults, was based on estimates of the maximum dimensions of fault rupture. Multiple sources of uncertainties were considered in estimating physical dimensions of maximum rupture on faults, including uncertainties in rupture length, rupture area, and displacement per event. The second approach considered historical data on the seismicity of the region. This approach was used primarily for areal source zones. For each of the sources included in the PSHA, the uncertainty in M_{max} is expressed as a probability distribution. The range of maximum magnitude for local fault sources is summarized in Table 2.2-17 (BSC 2004j, Section 4.3.4.1.1).

Earthquake recurrence relationships express the rate or annual frequency of different magnitude earthquakes occurring on a seismic source. Methods for developing these relationships are usually different for fault sources than for areal source zones. For fault sources, the expert teams used approaches based on estimates of fault slip rates, the average slip per event, and seismic moment rates. For areal sources, earthquake recurrence relationships were determined from the catalog of historical and instrumental earthquakes within 300 km of Yucca Mountain. For each of the local faults included in the PSHA, the expert teams' assessments of the range of slip rate and recurrence rate values are summarized in Table 2.2-17 (BSC 2004j, Section 4.3.4.1.1).

In the calculation of seismic hazard for the Yucca Mountain PSHA, earthquakes with magnitude M_w 5 and greater are incorporated. This is consistent with the approach taken in *Seismic Hazard Methodology for the Central and Eastern United States* (EPRI 1986) and with Appendix C of Regulatory Guide 1.165.

Seismic Source Characterization Assessments—The six expert teams considered a variety of alternative models and parameters in their characterization of seismic sources. Logic trees provided a mechanism for describing and quantifying the uncertainties. Key assessments for the PSHA are given as nodes of the logic tree, and alternative models or parameter values are given on the branches at each node. Weights are assigned to the alternative branches based on expert judgment regarding the relative credibility of the alternative models and parameters (CRWMS M&O 1998a, Section 4.1.1). An example logic tree for expressing the uncertainty in characterizing local fault sources is shown in Figure 2.2-21 and discussed in more detail in Section 2.2.2.1.4.

2.2.2.1.3.2 Ground Motion Characterization

The goal of the ground motion evaluation for the PSHA was to formulate attenuation models describing vibratory ground motion at the repository. Seven experts evaluated various proponent models. The experts provided point estimates of ground motion for a suite of prescribed faulting cases, and source-to-site distances. These point estimates were subsequently regressed to ground motion attenuation equations. Ground motion measures that were assessed consisted of peak ground acceleration, response spectral values for specified spectral frequencies and peak ground velocity (random horizontal and vertical components). For each point estimate, the experts provided an interpretation of the median ground motion, its variability (i.e., aleatory variability), and the uncertainty (i.e., epistemic uncertainty) in each. The range of point estimates was designed to sample the magnitude-distance-faulting space at Yucca Mountain in sufficient detail to provide a robust regression (BSC 2004j, Section 4.3.4.1.3).

The ground motion estimates and, thus, the resulting attenuation relationships were developed for a reference rock outcrop. This reference rock outcrop was defined to have geotechnical conditions identical to those of the rocks that available data indicated were present at 300 m depth. Parameter values were determined on the basis of seismic refraction, vertical seismic profiling, and laboratory testing studies (BSC 2004h, Section 6.3.3.1.1; Schneider et al. 1996, Section 5). The reference rock outcrop was used because site-specific data on the velocities and dynamic properties of the site rock and soil were limited at the time of the PSHA (BSC 2004j, Section 4.3.4.1.3). For design analyses and analyses supporting performance assessment, the effect on ground motion of the material between the reference rock outcrop level and the earth's surface (i.e., the site response) is taken into account through a site-response model. Geotechnical investigations, carried out after the completion of the PSHA, provided data to characterize the velocity and dynamic material properties of the site materials in support of the site-response modeling (Sections 2.3.4.3.2.2 and 1.1.5) (BSC 2004i, Sections 6.2.3 and 6.2.4; BSC 2008, Section 6.4). The relation between the reference rock outcrop and the repository locations at which site-specific ground motions are needed is shown in Figure 2.3.4-4.

Proponent Models—The experts computed their ground motion point estimates by considering existing proponent models. The proponent models fell into several classes: empirical attenuation relationships, hybrid-empirical, point source numerical simulations, finite-fault numerical simulations, and blast models. The experts evaluated the models in terms of their implications for ground motion at Yucca Mountain (BSC 2004j, Section 4.3.4.1.3). Each expert evaluated the proponent models, weighted the predictions of the various models or model classes, developed conversion factors to adjust model results to Yucca Mountain conditions (if necessary), developed scaling factors to obtain ground motion measures not directly addressed in a given model, and applied professional judgment to determine the point estimates.

The empirical models used for the PSHA resulted from regression analyses of strong-motion records primarily from California earthquakes. Because of possible differences in seismic source, propagation path, and site characteristics between the regions for which the empirical models were developed and Yucca Mountain, these empirical relationships required adjustments so that they would apply to conditions in the Yucca Mountain region. The hybrid empirical model was derived from these relationships and implicitly included conversion factors that must be separately applied to the empirical relationships (BSC 2004j, Section 4.3.4.1.3).

The blast models are based on empirical records from underground nuclear explosions at the Nevada Test Site (Schneider et al. 1996, pp. 3-15 to 3-17). Three blast models were assessed, each with a different approach to account for differences in earthquake sources and explosion sources (BSC 2004j, Section 4.3.4.1.3).

The numerical simulations were tailored to Yucca Mountain conditions and required no adjustments to correct for source, path, or site conditions in a different region (e.g., California). This is in contrast to the adjustments needed to apply empirical models in the Yucca Mountain region. The point source models were the simplest numerical models and also the best understood. The finite-fault numerical simulations were derived from the six models evaluated in the scenario earthquake modeling study. The experts chose three model approaches for their analyses: a stochastic method with omega-squared (ω^2) subevents, a composite fractal source method, and a broadband Green's function method (BSC 2004j, Section 4.3.4.1.3).

Conversion Models and Scaling Factors—Depending on the nature of the data sets upon which they were based, the empirical relationships typically represented source, path, and site conditions different from those encountered at Yucca Mountain. Suites of conversion factors were computed as part of the study. They were developed using the results of numerical finite-fault simulations, stochastic point source simulations, and empirical attenuation relationships. The factors included corrections for the following:

- **Source**—Western United States compressional and strike-slip seismic sources to Yucca Mountain extensional seismic sources

- **Crust**—Western United States crust to Yucca Mountain crust

- **Site**—Western United States surface conditions to Yucca Mountain reference rock outcrop surface conditions.

Additionally, many of the proponent models did not include the full range of ground motion parameters required. For example, not all of the empirical models included vertical ground motion. Thus, a variety of scaling factors were also developed and applied in the same manner as the conversion models to account for the full range of parameters (BSC 2004j, Section 4.3.4.1.3).

Attenuation Relationships—Each expert developed a set of point estimates for the defined cases covering different faulting styles, event magnitudes, source geometries, and source-site distances. The estimates comprised median ground motion, its variability, and the uncertainty in both. The estimates were determined directly from the models, the conversion factors, the scaling factors described above, and other judgments by the experts. These estimates were then parameterized in the form of attenuation relationships (BSC 2004j, Section 4.3.4.1.3).

The seven sets of attenuation relationships for horizontal ground motion predict median values that generally differ by less than a factor of 1.5. The experts' estimates of the aleatory variability in horizontal ground motions are generally within 0.1 natural log unit of each other. Their estimates of the epistemic uncertainty in the median horizontal ground motion (with one exception) and epistemic uncertainty in aleatory variability also generally vary by about 0.1 natural log unit. Vertical median ground motion models tend to be more variable between experts than the horizontal models. This larger variability is due to having fewer vertical proponent models available and much less validation for the numerical simulations. Estimates of epistemic uncertainty also tend to be larger for the vertical component than for the horizontal component (CRWMS M&O 1998a, p. 6-4).

2.2.2.1.3.3 Fault Displacement Characterization

Several approaches for characterizing the fault displacement potential were developed by the seismic source expert teams during the PSHA. These approaches were based primarily on empirical observations of the pattern of faulting from historical ruptures throughout the Basin and Range Province and at the site. Empirical data were fit by statistical models to allow use by the expert teams (BSC 2004j, Sections 4.3.1.2 and 4.3.4.1.2).

Both principal and distributed faulting are important to the assessment of the fault displacement hazard at the repository site. As described in Section 2.2.2.1.1.2, nine locations (with multiple assumed conditions at some locations) at or near the repository were identified to demonstrate the fault displacement methodology (Figure 2.2-12 and Table 2.2-15). These locations were chosen to represent the range of potential faulting conditions throughout the Yucca Mountain site. Some of these locations lie on faults that may experience both principal and distributed faulting. The other points are sites of potential distributed faulting (BSC 2004j, Section 4.3.4.1.2).

Two approaches were used to characterize the frequency of displacement events: the displacement approach and the earthquake approach. The displacement approach provides an estimate of the frequency of displacement events directly from the geologic history of displacement, as interpreted from observed feature-specific or point-specific data. The frequency of displacement events is based either on recurrence interval data or slip-rate data. The displacement approach does not distinguish between principal and distributed faulting (CRWMS M&O 1998a, Section 4.2.4.1).

The earthquake approach involves relating the frequency of slip events to the frequency of earthquakes on the various seismic sources defined by the seismic source characterization models for the ground motion assessment. Both approaches are used for assessing the fault displacement hazard for principal faulting and distributed faulting. For principal faulting, two approaches were developed to assess the probability of surface rupture given an earthquake. One is based on empirical data for the frequency of surface rupture, and the other is based on numerical randomization of the depth of rupture on the fault. Given that an earthquake produces principal surface rupture, the expert teams also assessed the probability that the extent of the rupture along the fault reaches the site for which fault displacement is being assessed. For distributed faulting, the expert teams assessed the probability that displacement on an earthquake source some distance from the site of interest will trigger displacement locally. Approaches to assess this probability were based on analysis of historical distributed ruptures and on the tendency of faults to slip either because of their orientation with respect to the present stress field or their orientation relative to the strike of the principal fault (CRWMS M&O 1998a, Section 4.2.4).

The basic formulation for probabilistic evaluation of the hazard from fault displacement is analogous to that developed for hazard from ground shaking. The fault displacement analysis conducted for the repository addresses how frequently fault displacement occurs and how large those displacements are. Hazard curves represent the hazard at a point and relate the amount of displacement in a single event to how often larger displacements occur (e.g., the frequency of exceeding a specified amount of displacement). The hazard curve is a plot of the frequency of exceeding a given fault displacement value. The frequency of exceeding a given fault displacement value can be computed as a product of the frequency at which displacement events occur on a structure located at the point of interest and the conditional probability of exceeding a specific displacement value (CRWMS M&O 1998a, Section 4.2.2).

The conditional probability of exceedance defines the probability that the amount of displacement occurring at a point during a single displacement event will exceed a specified amount. The probability can be considered to contain two parts: the variability of slip from event to event and the variability of slip along strike during a single event. The first part represents a distribution for the size of faulting events and is analogous to the earthquake magnitude distribution model used in the ground shaking hazard analysis. The second part represents the variation of the displacement at a point from the size of the event. This can be considered analogous to the lognormal distribution for ground motion about the median value predicted by an attenuation relationship for a specific magnitude and distance (CRWMS M&O 1998a, Section 4.2.5).

Various approaches were used to evaluate conditional probability of exceedance. Some approaches represent displacement variability in two distributions; others combine them into the single distribution function. The two-part approach is typically used with the earthquake approach for principal faulting hazard. The size measure used to describe the event was the maximum displacement in an earthquake and was typically assessed using empirical relationships between magnitude and maximum displacement. In some cases, trenching data was used to assess the maximum displacement events on a source fault. The second part of this approach is the assessment of the variability of slip at a point as a fraction of the maximum displacement in the event. The conditional probability of exceedance was then obtained by convolving these two distributions (CRWMS M&O 1998a, Section 4.2.5.1).

The single step approach for assessing the conditional probability of exceedance involved developing empirical distributions for the displacement data collected at Yucca Mountain by normalizing data from trenches. A variety of normalization parameters was developed, including the average displacement observed in a trench with multiple displacements, the average or maximum displacement expected for a fault based on its dimension, and the cumulative displacement that has occurred on the features where the trench was located. These empirical distributions were then fit with statistical models to derive the conditional probability of exceedance for use in the displacement hazard computation (CRWMS M&O 1998a, Section 4.2.5.2, Appendix H).

2.2.2.1.4 Probability Model Parameters
[NUREG-1804, Section 2.2.1.2.2.3: AC 4]

Evaluations of seismic source characteristics, earthquake ground motion, and fault displacement involve interpretations of data. The interpretations have associated uncertainties related to the ability to fully resolve various hypotheses and models in light of the available data. In the PSHA, a formal expert elicitation process was used to develop inputs that specifically included estimates of variability and uncertainty in interpretations (BSC 2004j, Section 4.3.4).

Parameters and their associated uncertainties were incorporated into the PSHA using a logic tree methodology. The logic tree formulation for seismic hazard analysis involves setting out the sequence of assessments that must be made to perform the analysis and then sequentially addressing the uncertainties in each assessment. Probabilities are assigned to each branch to represent the relative likelihood or degree of belief that the branch represents the correct value or state of the input parameter. These probabilities are assessed conditionally on the assumption that all the branches leading to that node represent the true state of the preceding parameters. Because they are conditional probabilities for an assumed mutually exclusive and collectively exhaustive set of values, the sum of the conditional probabilities at each node is unity. The probabilities depend strongly on expert judgment (subjective probabilities) because the available data are too limited to allow for objective statistical analysis, and scientific judgment is needed to weigh alternative scientific interpretations of the available data. The logic tree approach simplifies these subjective assessments. For a given branch on the logic tree, the uncertainty in a parameter of interest is evaluated by assuming that the other parameters in the branch leading up to the parameter of interest are known with certainty. Thus, the nodes of the logic tree are sequenced to provide for the conditional aspects or dependencies among the parameters and to provide a logical progression of assumptions from the general to the specific in defining the input parameters for an evaluation (CRWMS M&O 1998a, Section 4.1.1).

A series of logic trees was used to represent the uncertainty in defining and characterizing the relevant seismic sources for the PSHA. Each expert team developed its own logic tree, and the results of all the teams were aggregated with equal weight. A representative logic tree for characterizing local fault sources is shown in Figure 2.2-21. Interpretations in the logic tree usually are ordered from general to specific. The order of the interpretations, however, is dictated primarily by convenience in dealing with interdependencies in the characterization. After the logic tree is constructed, the order of the nodes can be changed, with the dependent assessments typically placed to the right, and the independent assessments typically placed to the left (CRWMS M&O 1998a, Section 4.1.1).

The ground motion characterization required coordination with the seismic source characterization teams. Based on the seismic source descriptions developed, the ground motion experts each developed a series of estimates of ground motion for a defined suite of earthquake magnitudes and distances, fault geometries, and faulting styles. The estimates included the median ground motion and its variability and the scientific uncertainty on both. These point estimates were fitted to yield attenuation equations as a function of all four parameters (CRWMS M&O 1998a, Section 5.1).

A key issue in characterizing ground motion attenuation at Yucca Mountain was the applicability of standard western United States attenuation models to the Basin and Range Province. Furthermore, significant differences may exist in the seismic source, regional crustal, and shallow site properties for Yucca Mountain as compared to the average source, path, and site properties represented in the western United States strong motion data set. An issue that the experts addressed was whether, or to what degree, these differences could affect median ground motion or variability in ground motion expected at Yucca Mountain compared to those predicted by proponent models based primarily on

California data (CRWMS M&O 1998a, Section 5.2, p. 5-7). The judgments of these experts are reflected in the weights they assigned to the alternative proponent models (CRWMS M&O 1998a, Section 5.5).

2.2.2.1.5 Uncertainty in Event Probability

[NUREG-1804, Section 2.2.1.2.2.3: AC 5]

An essential aspect of conducting the PSHA as a formal expert elicitation is the incorporation of uncertainties. A key mechanism for quantifying uncertainties is the use of multiple expert evaluations. The process used to select the experts; facilitate their interaction and mutual training; and elicit, refine, and document their evaluations is designed to support proper characterization of uncertainties (CRWMS M&O 1998a, Section 2).

Identifying and assessing the uncertainties in seismic source and fault displacement characterization was an important objective of the PSHA. This aspect of the evaluation was designed to capture uncertainty both in the models used to characterize seismic sources and in the parameter values used in the models. The experts, who were from both within and outside the Yucca Mountain Project, represented a range of experience and expertise relevant to performing the evaluations. A deliberate process was followed in facilitating interactions among the experts, training them to express their uncertainties (while recognizing and compensating for common cognitive biases), and eliciting their interpretations (Section 5.4). The resulting evaluations, therefore, provide reasonable expectation that the knowledge and uncertainties about seismic source and fault displacement characterization at the repository site relevant to the PSHA were captured and expressed in the seismic hazard results (CRWMS M&O 1998a, Section 1.5.1).

In the PSHA, two types of uncertainty, epistemic and aleatory, are distinguished and treated differently. For each combination of assumptions, hypotheses, models, and parameter values representing epistemic uncertainties with their associated weights, integration is carried out over aleatory variability to obtain a single hazard curve. Repeating this process for all the combinations results in a suite of hazard curves that are then characterized by mean, median, and fractile curves. The mean and median hazard curves represent the central tendency of the calculated exceedance frequencies. The separation among fractile curves represents the net effect of epistemic uncertainties incorporated into the analysis (CRWMS M&O 1998a, Section 7.1.1).

2.2.2.2 Igneous Activity

[NUREG-1804, Section 2.2.1.2.2.3: AC 1, AC 2, AC 3, AC 4, AC 5]

This section describes the probabilistic volcanic hazard analysis (PVHA) (CRWMS M&O 1996) conducted for the Yucca Mountain site, which describes the estimated annual frequency of intersection of the repository by an igneous event and the methods used to develop that estimate. This section summarizes the process used for the PVHA and the technical bases used by the PVHA experts to estimate the annual frequency of intersection. The process followed project procedures for conduct of an expert elicitation, and the project procedure that was in effect was consistent with NRC expert elicitation guidance (NUREG 1563; Kotra et al. 1996).

An overview of the geologic setting is provided, and the igneous framework of the Yucca Mountain region is reviewed. The definition of a volcanic event and the spatial and temporal patterns of igneous activity in the region that formed the basis for expert interpretations and assessments of uncertainty are summarized. The approach used to characterize igneous events is described in terms of the variabilities and uncertainties in igneous event parameters that were estimated so they could be included in the volcanic hazard results, which are the estimates of the annual frequency of intersection provided by the PVHA experts (CRWMS M&O 1996, Section 4.1). The estimates were combined to produce an aggregate hazard estimate that described the mean annual frequency of intersection of the repository by a volcanic event (CRWMS M&O 1996, Section 4.3).

The hazard estimate was updated, using methods consistent with those used by the PVHA experts, to account for effects of repository design differences (BSC 2004k, Table 7-1). In addition, effects of information that became available after the conclusion of the PVHA (Blakely et al. 2000; O'Leary et al. 2002; Hill and Stamatakos 2002) on the hazard estimate have been evaluated (BSC 2004k, Section 6.5.4.1). The results of the analyses indicate that repository design differences between the design used for the PVHA and that used in the license application have small effects on the mean annual frequency of intersection (BSC 2004k, Section 7.1). The results also show that the effects of buried volcanic centers on the hazard estimate are modest (Section 2.3.11.2.2.6; BSC 2004k, Section 6.5.4.2.2), and the updated hazard estimate is robust and suitable for use in the license application and supporting TSPA calculations.

Igneous activity at the repository is evaluated in terms of the probability that a future igneous event could intersect the repository and the consequences or effects of such an event on the performance of the repository system following permanent closure. The regulations pertinent to the disposal of high-level radioactive wastes in a geologic repository at Yucca Mountain specify that the performance assessments must consider events that have at least one chance in 10,000 of occurring within 10,000 years of disposal (proposed 10 CFR 63.342(a)). This section describes the probability of a future igneous event intersecting the repository, the technical basis for the probability estimate, the probability model support including alternative estimates of the intersection probability, the probability model parameters, the uncertainties associated with the probability estimate, and the conclusion that the probability of an igneous event occurring at Yucca Mountain is high enough to be included in the TSPA. The evaluation of the consequences of an igneous event is presented in terms of two igneous modeling cases, the igneous intrusion model case and the volcanic eruption model case, which are described in Sections 2.3.11.3 and 2.3.11.4, respectively.

2.2.2.2.1 Probability of an Igneous Event Intersecting the Repository
[NUREG-1804, Section 2.2.1.2.2.3: AC 1, AC 4]

The possibility that igneous or volcanic activity could affect a repository at Yucca Mountain was recognized when the site was selected for characterization in the late 1970s. An expert elicitation, the *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada* (CRWMS M&O 1996) was conducted to estimate the probability of future igneous activity at the Yucca Mountain site. Comprehensive data collected over two decades was used to understand the temporal and spatial characteristics of basaltic volcanism of the Yucca Mountain region and provided the primary input to the expert elicitation (BSC 2004k, Section 6.3.1).

The primary result of the expert elicitation was an estimate of the mean annual frequency of intersection of the repository by a future basaltic dike.

2.2.2.2.1.1 Definition of Event

The likelihood of future igneous activity at the repository was estimated in terms of the probability of occurrence of a future igneous event. Hence, the definition of an igneous event is a key consideration in the development of the probability estimate. The PVHA experts defined a volcanic event to be a spatially and temporally distinct batch of magma ascending from the mantle through the crust as a dike or system of dikes (CRWMS M&O 1996, Appendix E). The physical manifestations of a volcanic event include the dike or dike system and any surface eruption deposits. For the purposes of probability models, a volcanic event is defined as a point (x, y) in space representing the expected midpoint of the dike system involved in the magma ascent. The dike system associated with the volcanic event is represented in the probability model by a line element defined in terms of a length, azimuth, and location relative to the point event (Figure 2.2-22). The term “dike length” used in the PVHA and in this section when discussing volcanic events refers to the total length of the dike system associated with the volcanic event. The phrase “intersection of the repository footprint by a dike” refers to intersection of the waste emplacement area of the repository by the line element representing the dike system associated with the volcanic event (BSC 2004k, Section 6.3.2).

The PVHA experts assumed volcanic events to have both subsurface (intrusive) and surface (extrusive or eruptive) components. The output of the PVHA is the annual frequency of intersection of the proposed repository by an intrusive basaltic dike (Section 2.2.2.2.1.2; CRWMS M&O 1996, Section 4.2, Figure 4-32). The proportion of the intersections that include eruption through the repository was calculated (Section 2.2.2.2.1.3; SNL 2007k, Section 7.1) based on analogue information using the PVHA probability as a basis (SNL 2007l, Section 6.3.3).

Subsequent studies of the sensitivity of the frequency of intersection to alternative conceptual models (BSC 2004k, Section 6.3.1.6), to the presence of additional buried volcanic centers (BSC 2004k, Section 6.3.1.7), and to alternative estimates of the probability of intersection (BSC 2004k, Section 6.3.1.8) have shown that the estimate of the frequency of intersection is robust and shows only minor sensitivity to the parameters investigated.

2.2.2.2.1.2 Probability of Intrusion

The probability of intrusion into the repository without consideration of eruption through the repository is presented as the annual frequency of intersection of the repository by a basalt dike. The computed mean annual frequency of intersection of the repository footprint by a dike is 1.7×10^{-8} (BSC 2004k, Table 7-1), as compared to 1.5×10^{-8} obtained in the PVHA for an earlier repository footprint (CRWMS M&O 1996, p. 4-10). The PVHA estimate of the frequency of intersection considered regional and local spatial and temporal patterns of igneous activity as the basis to define an igneous event for purposes of estimating the volcanic hazard (annual frequency of intersection) (CRWMSM&O 1996, Section 3.1.1). Sensitivity studies (Brocoum 1997; CRWMS M&O 1998b, Chapter 6) show that the addition of several volcanic events located within already defined volcanic source zones does not significantly impact the results of the PVHA. Incorporation of alternative conceptual models in the PVHA (BSC 2004k, Section 6.3.1.6) and subsequent studies of the sensitivity of the hazard estimate to the presence of additional buried volcanic centers (BSC 2004k, Section 6.3.1.7) and to alternative estimates of the probability of intersection (BSC 2004k, Section 6.3.1.8) have shown that the estimate of the frequency of intersection is robust and shows only minor sensitivity to the parameters investigated. These mean annual frequencies exceed the regulatory threshold for exclusion of an igneous event based on probability, and, therefore, the consequences of an igneous intrusion event at the repository must be evaluated in the TSPA (SNL 2008b, Section 6.5.1). The computed 5th and 95th percentiles of the uncertainty distribution for frequency of intersection are 7.4×10^{-10} and 5.5×10^{-8}, respectively, as compared to 5.4×10^{-10} and 4.9×10^{-8} obtained in the PVHA (CRWMS M&O 1996, p. 4-10; BSC 2004k, Section 6.5.3.1). Although the repository design has changed several times since the completion of the PVHA, the mean annual frequency of intersection of the repository footprint shows little sensitivity to the design changes (BSC 2004k, Sections 6.5.2.1 and 7.1; Section 2.3.11.2.2.3).

Figure 2.2-23a shows the computed distributions for the frequency of intersection aggregated over the 10 PVHA experts' interpretations, together with the median and mean values obtained for each expert's interpretation. Figure 2.2-23b compares the 5th to 95th percentile range for frequency of intersection obtained for each expert's interpretation with that for the aggregate distributions. The major contribution to the uncertainty in the frequency of intersection is the statistical uncertainty in estimating volcanic event rates (CRWMS M&O 1996, Figure 4-33). The second largest contribution to uncertainty is modeling the frequency of future events. Although differences exist between the interpretations of the 10 experts, most of the uncertainty in the computed frequency of intersection is due to the average uncertainty that an individual expert expressed in developing the appropriate PVHA model (CRWMS M&O 1996, Section 4.3).

2.2.2.2.1.3 Probability of Eruption

Every igneous intrusion that intersects the repository includes an eruption at some location along the dike. The calculation of the probability of an eruption within the repository footprint is based on analogue information about dike lengths, number and spacing, and conduit numbers, conduit size and spacing (SNL 2007l, Table 7-1) and is provided as a point value of 0.28. The value represents the fraction of intersections that include at least one eruption within the repository footprint (SNL 2007k, Section 6.3, Step 5, and Appendices A and E.6). Uncertainty in the eruption probability arises primarily from the use of stochastic input parameters that define the uncertainty in the characteristics of a volcanic event (SNL 2007l, Sections 6.5.1 and 7.2 and Table 7-1; SNL 2007k, Section 6.4), and from different concepts of an event (described in Section 2.3.11.4.4.1).

2.2.2.2.1.4 Process Used for Probabilistic Volcanic Hazard Analysis

To assess the likelihood of a future igneous event disrupting a repository at Yucca Mountain, a formal elicitation process that utilized the assessments of 10 expert panel members was implemented. This process ensured that a wide range of alternative interpretations and the associated uncertainties were considered. The judgments of the expert panel members were equally weighted and subsequently combined to produce a probability distribution of the annual frequency of intersection of a basaltic dike with the repository footprint (BSC 2004k, Section 6.3.1.5).

The PVHA was conducted prior to the issuance of NUREG-1563 (Kotra et al. 1996), which provides NRC guidance on the use of expert elicitation in the HLW program. However, the NRC guidance was available in draft form at the time of the PVHA (CRWMS M&O 1996, Section 2.1.1), and the process followed for the PVHA was consistent with the draft guidance. The PVHA methodology was also consistent with the guidance provided by the Senior Seismic Hazard

Analysis Committee (Budnitz et al. 1997) in a study sponsored by the DOE, NRC, and Electric Power Research Institute (CRWMS M&O 1996, Section 2.1.1).

The PVHA panel of experts convened between February and December 1995. A technical facilitator–integrator led carefully structured, intensive interactions among the panel members, including workshops and field trips. The primary objective of the workshops was to ensure the experts' understanding of alternative volcanic hazard models and the available data on which to base their technical assessments. The first three workshops focused on the data, volcanic hazard models, and interpretations relevant to the PVHA and included presentations of data and interpretations by technical specialists from a variety of research institutions. Formal individual elicitation interviews were held following the third workshop. During the fourth workshop, the experts reviewed the preliminary assessments developed by each of the 10 panel members, after which the individual elicitations were revised based on feedback received. Two field trips held during the course of the PVHA provided the opportunity for the panel members to observe geologic relationships pertaining to eruptive style, the definition of volcanic events, and the distribution and timing of volcanic activity in the Yucca Mountain region. In all the interactions, it was made clear that one of the purposes of the PVHA was to identify and understand uncertainty, not to eliminate it, and that disagreement was expected and accepted. In developing the individual assessments, each expert's role was an informed technical evaluator of data, rather than a proponent of a particular interpretation (BSC 2004k, Section 6.3.1.2).

Hazard models were developed by each of the 10 experts for the PVHA. Each model was presented in the form of a logic tree. The logic trees explicitly incorporated the uncertainty in selecting appropriate probabilistic models and model parameters to describe the spatial and temporal occurrence of future volcanic events in the vicinity of the repository site and to describe the length and azimuth of basaltic dikes associated with these events. The PVHA computation consisted of calculating the rate density of volcanic events on a 1 km by 1 km grid throughout the region defined by the local source zones. Similarly, the conditional probability of intersection was computed for the same grid of points. Multiplying the rate density of events by the conditional probability of intersection at each point in the grid, then summing up all points in the grid yields the annual frequency of intersection. The computation process was repeated for all possible combinations of event geometries, temporal models, time periods, spatial models, source zone definitions, smoothing parameters, event counts, and statistical distributions in rate estimates defined by the logic tree developed for each expert. The discrete distributions were used to compute the expected frequency of intersection and the statistics of the uncertainty in the frequency of intersection (CRWMS M&O 1996, Section 4.1). The update of the frequency of intersection considered a revised repository design and used a 0.5 km × 0.5 km grid to calculate the rate density (BSC 2004k, Section 6.5.1.1).

The aggregation approach process of combining individual assessments made by the expert panel members was used in the PVHA, and equal weight was applied to each expert's distribution (CRWMS M&O 1996, Sections 2.2.11 and 4.2). Aggregation of the individual assessments was necessary to arrive at a calculated result that could be used for subsequent consequence and TSPA analyses.

2.2.2.2.2 Technical Bases of Probability Estimates
[NUREG-1804, Section 2.2.1.2.2.3: AC 2]

Volcanism studies for repository siting purposes began in 1979 in the Yucca Mountain region. Researchers from many organizations, including universities, conducted these studies. DOE-sponsored investigations are comprehensive and include geologic mapping; geophysical investigations; physical, petrological, geochemical, and geochronological investigations of dikes, conduits, and erupted materials; numerical modeling of magma ascent through dikes and in conduits and atmospheric dispersal and deposition of pyroclastic material onto the ground surface. Data from these studies were evaluated to identify the igneous-related FEPs that might affect the repository. Possible effects include igneous intrusion into the repository, interaction with EBS components, and development of one or more eruptive conduits to the surface intersecting the repository.

2.2.2.2.2.1 Geologic Setting

Between about 15 and 11 million years ago, volcanism in the Yucca Mountain region was dominated by a major episode of caldera-forming, silicic volcanism, forming the southwestern Nevada volcanic field (Sawyer et al. 1994). Silicic volcanism was approximately synchronous with a major period of crustal extension or stretching, which occurred between 13 and 9 million years ago (Sawyer et al. 1994, Figure 4). Volcanism in the Yucca Mountain region peaked between 11 and 13 million years ago with the eruption of the rhyolitic units of the Paintbrush and Timber Mountain Groups (Sawyer et al. 1994, Table 1).

About 9 to 10 million years ago, the character of volcanism changed from silicic (rhyolitic) to mafic (basaltic), and the volume of material erupted decreased dramatically compared to the final rhyolitic eruptions. Silicic volcanism has not occurred in the region in the last 7 or 8 million years and, as a result, is not included as part of the igneous conceptual model. Basaltic volcanism continued from the late Miocene (about 7 million years ago) through the Quaternary period. The youngest nearby volcano (the Lathrop Wells Cone) erupted approximately 80,000 years ago (BSC 2004k, Section 6.2 and Table 6-2). Since the late Miocene, the volume of erupted material has generally decreased (Perry et al. 1998, Chapter 2); volcanism in the Quaternary has been limited to small volume basaltic centers (BSC 2004k, Section 6.1.1.1).

2.2.2.2.2.2 Temporal and Spatial Models Used in Probabilistic Volcanic Hazard Analysis

The characteristics of a future volcanic event are expected to be similar to those of Quaternary basaltic eruptions in the region. The event probabilities obtained through the PVHA are considered to be applicable to the potential occurrence of an event that would include one or more dikes in the subsurface, combined with some type of extrusive activity on the surface (BSC 2004k, Sections 5.1 and 5.2).

Temporal models describe the frequency of occurrence of volcanic activity and include homogeneous and nonhomogeneous models. Many of the PVHA experts used homogeneous Poisson models to define the temporal occurrence of volcanic events. These models assume a uniform rate of volcanism based on the number of volcanic events that occurred during various periods in the past. Nonhomogeneous models were used by some experts to consider the possibility that volcanic events are clustered in time or to describe the possible waning or waxing of volcanic activity in the region during the period of time the experts believed was relevant to hazard analysis (BSC 2004k, Section 6.3.1.3).

Spatial models describe the spatial distribution (location) of future volcanic activity. The most common PVHA models considered the future occurrence of volcanoes to be homogeneous within particular defined regions or source zones. Source zones were defined based on several criteria, including but not limited to the areal distribution of observed basaltic volcanoes (especially volcanoes from the past 5 million years), structurally controlled regions, regions defined based on geochemical affinities, and tectonic provinces. Nonhomogeneous parametric areal distributions of future volcano occurrences were also modeled (e.g., one model assumes that the location of future volcanoes will follow a bivariate Gaussian distribution based on the location of volcanoes in Crater Flat). Finally, nonhomogeneous, nonparametric spatial density models were used by some experts to assess the areal distribution of volcanoes. These models make use of a kernel density function and smoothing parameter based on locations of existing centers to obtain the spatial distribution for the location of future volcanoes (BSC 2004k, Section 6.3.1.3).

2.2.2.2.3 Probability Model Support
[NUREG-1804, Section 2.2.1.2.2.3: AC 3]

Tectonic and igneous models supporting a conceptual framework of igneous activity in the Yucca Mountain region are based on field investigations and evaluations of natural analogues, and are consistent with the volcanic and tectonic history of the region. The temporal and spatial models developed by the expert panel members that lead to the individual PVHA models were also based on the available information from DOE investigations as well as information provided by the expert panel members. Conceptual models presented in the PVHA were based on available information. Relationships between volcanic source zones defined in the PVHA and structural features of the Yucca Mountain region are described in additional studies published after completion of the PVHA (e.g., Wernicke et al. 1998; Smith, Keenan et al. 2002; Connor et al. 2000; Fridrich 1999; Fridrich et al. 1999; and BSC 2004k, Section 6.3.1.6, Table 6-4).

2.2.2.2.3.1 Geologic Basis for the Probabilistic Volcanic Hazard Analysis

The PVHA combined multiple alternative conceptual models into a single distribution that captured the uncertainty in the expert conceptual models of the physical behavior of volcanism in the Yucca Mountain region. For regional volcanism, no single base-case conceptual model is appropriate because the underlying physical processes that control the precise timing and location of volcanic events within a particular region remain uncertain (BSC 2004k, Section 6.3.1.6).

Interpretations of how and where magmas form and what processes control the timing and location of magma ascent through the crust form the conceptual model of volcanism. In general, the PVHA experts viewed the Yucca Mountain region as part of the same extensional tectonic and volcanic regime as the rest of the southern Great Basin portion of the Basin and Range Province. Some members of the panel also noted the possible additional influence of the Walker Lane structural zone on volcanism. The smaller volumes of erupted basalt in the Yucca Mountain region since the

Miocene reflects waning of both tectonism and magmatism in this part of the Basin and Range Province (BSC 2004k, Section 6.3.3).

Some PVHA experts distinguished between deep (mantle source) and shallow (upper crustal structure and stress field) processes when considering different scales (regional and local) of spatial control on volcanism. The PVHA experts generally view volcanism in the Yucca Mountain region as a regional-scale phenomenon resulting from melting processes in the upper lithospheric mantle. The mechanism of mantle melting in the Yucca Mountain region is related to a complex combination of processes, including the effect of residual heat in the lithospheric mantle, local variations in volatile (water) content, variations in mantle mineralogy and chemistry, and the effect of regional lithospheric extension. Formation of small volumes of alkali basalt, the composition observed in the region, reflects the melting of a relatively small percentage of parent mantle material (e.g., the lowest melting point fraction) (BSC 2004k, Section 6.3.3).

Analyses of magmatic processes in the Yucca Mountain region generally indicate that the magnitude of mantle melting has significantly decreased since the middle Miocene. The analyses also suggest that melts in the past few million years were generated within relatively cool ancient lithospheric mantle (compared to asthenospheric mantle), which is a factor that may contribute to the relatively small and decreasing volume of basaltic melt erupted in the Yucca Mountain region since the Miocene period (BSC 2004k, Section 6.3.3).

On a more local and shallow crustal scale, the PVHA experts concluded that volcanism is correlated with zones of past or present crustal extension, and once dikes feeding volcanoes enter the shallow upper crust, their location and orientation are influenced by the orientation of the local stress field and the presence of faults that may locally control vent location and alignment. Evidence cited for these two conclusions includes several northeast-oriented vent alignments in the Yucca Mountain region and the association of eruptive centers with known or inferred faults (BSC 2004k, Section 6.3.3).

The Quaternary volcanoes in the Crater Flat basin and their proximities to Yucca Mountain (Figure 2.2-24) result in the Crater Flat cluster playing a major role in assessing the potential for future volcanism at Yucca Mountain. Research on the Crater Flat structural domain, published largely since the PVHA was conducted (Fridrich 1999), provides evidence that the northeastern and southwestern portions of the basin have different extensional histories that may have influenced the location of basaltic volcanism within the basin (BSC 2004k, Section 6.4).

The correlation between the structurally active portion of the Crater Flat basin and sites of volcanism within the basin indicated to the PVHA experts that Yucca Mountain is near but not within a local volcanic zone that may produce small volumes of future volcanism. Although local source zones were chosen by PVHA experts based largely on the location of past volcanic events, the source zones correspond to the areas of highest cumulative extension and most active faulting in the Crater Flat basin (Fridrich et al. 1999, Figures 5 and 6), an association recognized by several of the PVHA experts. In cases in which local zones were defined, the zones were restricted to the southwestern portion of the Crater Flat basin or defined as elongated, northwest-trending belts that included the southwestern portion of the basin and stretched to the Timber Mountain area. The local zones did not include the northeastern portion of the Crater Flat basin, in which the repository is located. Based on structural analysis and the past patterns of the close association of volcanism and extension, the eastern boundaries of local volcanic source zones defined in the PVHA separate more tectonically active and less tectonically active portions of the Crater Flat basin and are reasonable assessments of the eastern extent of volcanism expected in the future (BSC 2004k, Section 6.4.2).

In terms of probability calculations, the volcanic source zones defined in the PVHA (Figure 2.3.11-4) represent local regions of higher event frequency (southwestern Crater Flat), while northeastern Crater Flat (which includes Yucca Mountain) falls within a regional background source zone of lower event frequency (BSC 2004k, Figures 6-7a and 6-7b). According to the intersection probability models used in the PVHA, two mechanisms can generate a disruptive volcanic event at Yucca Mountain: either (1) a volcanic event is generated within a local source zone (higher probability event) to the west of Yucca Mountain and has the appropriate location and dike characteristics (length and azimuth) to intersect the repository; or (2) a volcanic event is generated within a regional background zone (lower probability event) and intersects the repository (BSC 2004k, Section 6.4.2).

Since both source zones are used to define the probability of intersection of a volcanic event with the repository, spatial event frequencies that lie between local source zone values and regional background values are obtained. This is appropriate for a site that lies outside of a local volcanic source zone but near enough to possibly be affected by dikes generated within the source zone (BSC 2004k, Section 6.4.2).

Many models of the PVHA experts related the areas of greatest likelihood for future volcanic activity to the region where previous volcanism has occurred and in which extensional deformation has been and continues to be greatest (e.g., to the southwestern portion of the Crater Flat basin) (BSC 2004k, Section 6.4.2). Given that the southern and southwestern portions of the Crater Flat basin are the most extended and that the locus of post-Miocene volcanism in the Crater Flat basin lies in the south and southwestern portion of the basin, volcanic source zones defined in the PVHA and centered in southwestern Crater Flat are consistent with the tectonic history and structural features of the Crater Flat structural domain (BSC 2004k, Section 6.4.2).

Additional studies to increase confidence in site characterization results related to igneous activity have been completed since the PVHA (CRWMS M&O 1996) was concluded. These studies included a high-resolution aeromagnetic survey conducted in 2004, which was designed to optimize detection of buried basalt or basalt intrusions. The results of the aeromagnetic survey were used to design a drilling program to identify the sources of magnetic anomalies (Perry et al. 2005). The youngest basalt encountered by drilling (drill hole VA-2, Figure 2.2-24) was dated at 3.9 million years old (Table 2.3.11-3) and is located in the northern Amargosa Desert. No post-Miocene basalt was identified to the east of the repository in Jackass Flats. The results of the aeromagnetic survey and drilling program indicate that the essential characteristics of the age and location of basaltic volcanism near Yucca Mountain were fundamentally understood when the PVHA was completed in 1996 (Section 2.3.11.2.1.1).

2.2.2.2.3.2 Alternative Estimates of the Intersection Probability

Several alternative estimates of the intersection probability (the annual probability of a volcanic event intersecting the repository footprint) were presented between 1982 and 2000 (Table 2.2-18 and Table 2.3.11-4), including the mean intersection probability estimated in the PVHA. These values cluster at slightly greater than 10^{-8} per year, providing confidence that the probability estimate is robust. This confidence is warranted given the range of alternative temporal and spatial models and event geometries considered in the probability calculations (BSC 2004k, Section 6.3.1.8).

In the alternative estimates of the intersection probability developed between 1982 and 2000, volcanic events in hazard calculations were represented as both points and lines, as shown in Table 2.3.11-4. For point events, volcanic source zone areas or the repository area are adjusted to account for the fact that volcanic events have dimension due to the length of associated dikes. The shorter the dike length, the more comparable the intersection probability results are to calculations representing volcanic events as points. Probabilities near 10^{-7} intersections per year reflect unusually small volcanic source zone areas or unusually long event lengths (BSC 2004k, Section 6.3.1.8).

2.2.2.2.4 Probability Model Parameters
[NUREG-1804, Section 2.2.1.2.2.3: AC 4]

Considerable uncertainty is associated with assessing very low probability events, such as an igneous event intersecting Yucca Mountain. This uncertainty is associated with selecting the appropriate models and model parameters, and possible alternative interpretations as a result of the available data. For the PVHA, a logic tree methodology was used to incorporate the uncertainty in modeling the spatial and temporal distribution of future volcanic events in the region surrounding the repository. The methodology involves setting out the sequence of assessments that must be made to perform the analysis and then addressing the uncertainties in each of these assessments in a sequential manner. The logic tree allows for alternative models, hypotheses, and parameter values to be weighted and incorporated into the analysis in a logical and transparent way. Thus, use of logic trees provides a convenient approach for separating a large, complex assessment into a sequence of smaller, simpler components that can be more easily addressed (CRWMS M&O 1996, Section 3.1.2).

The general logic tree structure used to represent the scientific uncertainties in the PVHA computation is shown in Figure 2.2-25. Each expert developed an individual logic tree and the results of all of the experts were aggregated with equal weight. The logic tree is structured to move from the assessment of the general framework (Figure 2.2-25) to specific assessments of individual volcanic zones and volcanic centers. The definition of a specific zone or estimation of the number of events that may have occurred at a volcanic center commonly depend on more general assessments of the appropriate time period or region of interest (CRWMS M&O 1996, Section 3.2.1).

Three key components of the volcanic hazard model are recognized: the estimated spatial distribution of future events; the estimated recurrence rate for future events; and the estimate of the spatial extent of an event if one occurs. Several approaches and models for estimating each of these components were used. To quantify uncertainty, the logic tree method was used (CRWMS M&O 1996, Section 3.1.2).

The logic tree is composed of a series of nodes and branches. Each node represents an assessment of a state of nature (e.g., alternative models or hypotheses) or an input parameter value that must be made to perform the analysis. Each branch leading from the node represents one possible discrete alternative for the state of nature or parameter value being addressed. The branches at each node are intended to represent mutually exclusive and collectively exhaustive sets of alternatives (CRWMS M&O 1996, Section 3.1.2).

Probabilities are assigned to each branch to represent the relative likelihood or degree of belief that the branch represents the value or state of the input parameter. These probabilities are assessed such that they are conditional on the assumption that all the branches leading to that node represent the state of the preceding parameters. Because the probabilities for an assumed mutually exclusive and collectively exhaustive set of values are conditional, the sum of the conditional probabilities at each node is unity. The probabilities depend strongly on expert judgment (subjective probabilities), objective statistical analysis, as well as scientific judgment to weigh alternative scientific interpretations of the available data. Thus, the nodes of the logic tree are sequenced to provide for the conditional aspects or dependencies among the parameters and to provide a logical progression of assumptions from general to specific in defining the input parameters for an evaluation (CRWMS M&O 1996, Section 3.1.2).

2.2.2.2.5 Uncertainty in Event Probability
[NUREG-1804, Section 2.2.1.2.2.3: AC 5]

The PVHA was conducted as a formal expert elicitation study to ensure that a wide range of approaches was used for the analysis and to properly quantify the associated uncertainties. A major objective of the PVHA was to explicitly characterize the uncertainties associated with the assessment of the probability of disruption of the repository by a volcanic event. This assessment of uncertainty was consistent with the guidance provided by the Senior Seismic Hazard Analysis Committee (Budnitz et al. 1997). A key concept used in the PVHA and in many similar studies is that the total uncertainty in the hazard result can be captured by careful consideration of uncertainties in the components of the assessment (CRWMS M&O 1996, Section 2.2.6).

The team for the PVHA ensured that aleatory and epistemic uncertainties were incorporated into the assessments. Aleatory uncertainties are considered nonreducible with the consideration of new data; epistemic uncertainties, however, are reducible with the introduction of new data. For example, the experts provided a probability distribution expressing their uncertainty in the length of dikes that might occur in the Yucca Mountain region. The experts included not only the aleatory uncertainty in length associated with an individual event, but also the epistemic uncertainty in the probability distribution for the population of dikes (e.g., mean length, standard deviation, maximum length) (Figure 2.2-25 contains other parameters assessed) (CRWMS M&O 1996, Section 2.2.6).

Each of the 10 experts independently arrived at a probability distribution for the annual frequency of intersection of the repository footprint by a dike that typically spanned about 2 orders of magnitude. From these individual probability distributions, an aggregate probability distribution for the annual frequency of intersection of the repository footprint by a dike was computed that reflected the uncertainty across the entire expert panel. The individual experts' distributions were combined using equal weights to obtain the aggregate probability distribution. The composite distribution spanned about 3 orders of magnitude for intersection frequency. The range in the mean frequencies of intersection for the individual experts' interpretations spanned about 1 order of magnitude. The variance for frequency of intersection defined by the composite distribution was disaggregated to identify the contributions from each of the sources of uncertainty, including variability between the experts' interpretations. Most of the uncertainty in characterizing the hazard arose from uncertainty in an individual expert's interpretation of the hazard rather than from differences in scientific interpretation between the experts. The probability distribution arrived at by the PVHA accounted for undetected events (buried volcanic events or intrusive events that never reached the surface). The undetected event frequency ranged from one to five times that of observed events, with most estimates in the range of 1.1 to 1.5 (BSC 2004k, Section 6.3.1.5).

The PVHA results indicated that the statistical uncertainty in estimating the event rate was the largest component of intraexpert uncertainty. The next largest uncertainty was uncertainty in the appropriate spatial model. Other important spatial uncertainties included the spatial smoothing distance, Gaussian field parameters, zonation models, and event lengths. The temporal issues of importance included the time period of interest, event counts at a particular center, and the frequency of hidden events (BSC 2004k, Section 6.3.1.5).

An important objective of a formal expert elicitation is to ensure that the probability distribution developed during the study adequately represents the diversity of views in the larger informed technical community. This objective was successfully achieved by completing actions that included selecting expert panel members who have a wide range of expertise and experience and who are associated with a variety of institutions (e.g., universities and national laboratories); conducting workshops that exposed the expert panel members to the variety of views of other panel members, as well as those of other technical specialists invited to speak at the workshops; by training the experts in ways to express their uncertainties (while recognizing and compensating for common cognitive biases); and by encouraging the experts to quantify uncertainties in their individual elicitations. Based on the implementation of these measures during the PVHA, as well as the confirmation with the expert panel members in the final workshop that their interpretations provided reasonable representations of the larger, informed technical community, the diversity in the total probability distribution was considered reasonable and representative (CRWMS M&O 1996, Section 2.2.8).

2.2.2.3 Early Waste Package and Drip Shield Failures
[NUREG-1804, Section 2.2.1.2.2.3: AC 1(1), AC 4]

This section summarizes the probability that a waste package or drip shield may fail due to manufacturing, or handling-induced defects at a time earlier than would be predicted by the mechanistic degradation models for a defect-free waste package or drip shield. The conceptual and technical bases for these events, along with the parameters used to calculate the probabilities of events, and the uncertainties associated with those parameters are described in detail in Section 2.3.6.

2.2.2.3.1 Definition of the Event

An early failure is defined as the through-wall penetration of a waste package or drip shield due to manufacturing- or handling-induced defects, at a time earlier than would be predicted by mechanistic degradation models for a defect-free waste package or drip shield (SNL 2007f, Section 1). Early failure of a defective waste package or a defective drip shield is modeled to occur at the time of repository closure (SNL 2007f, Section 6.5.2.).

2.2.2.3.2 Early Waste Package Failure Probability

Improper base material selection, improper heat treatment of the outer shell and lid, improper weld filler material, improper low plasticity burnishing, or mishandling of the waste package might have adverse consequences on waste package performance (SNL 2007f, Sections 6.2.3 through 6.2.3.7). The consequence common to these types of defects is an increased susceptibility to stress corrosion cracking. An evaluation to quantify the probability that a waste package is affected by at least one of these defect types was performed using Monte Carlo simulations. The resulting probabilities were then fit to a lognormal distribution. The resultant probability of waste package early failure is evaluated using a lognormal distribution with a mean of 1.13×10^{-4} per waste package, and an error factor of 8.17 (SNL 2007f, Section 6.5.1). This distribution has a median, 5th percentile, and 95th percentile of 4.14×10^{-5}, 6.10×10^{-6}, and 4.07×10^{-4} per waste package, respectively. For 11,629 waste packages, this corresponds to slightly more than one waste package on average that is affected by at least one of these defect types. These values are based on the waste package fabrication and handling processes described in Section 1.5.2, and necessarily imply the failures are independent (e.g., common cause failures are not likely) (SNL 2007f, Section 6.5.1). Details of technical bases for the probability estimates, including the parameters and data used and their associated uncertainties, are described in Section 2.3.6.6.

2.2.2.3.3 Early Drip Shield Failure Probability

Improper base metal selection, weld filler selection, improper heat treatment, and improper installation might have adverse consequences on drip shield performance (SNL 2007f, Sections 6.4.1, 6.4.2, 6.4.3 and 6.4.4). An evaluation to quantify the probability that a drip shield is affected by at least one of these defect types was performed using Monte Carlo simulations. The resulting probabilities were then fit to a lognormal distribution. The resultant probability of early failure is evaluated using a lognormal distribution, with a mean of 2.21×10^{-6} per drip shield and an error factor of 14 (SNL 2007f, Section 6.5.1). This distribution has a median, 5th percentile, and 95th percentile of 4.3×10^{-7}, 7.86×10^{-8}, and 6.97×10^{-6} per drip shield, respectively. For approximately 11,600 drip shields, this corresponds to well less than one drip shield on average. These values are based on the drip shield fabrication and handling processes described in Section 1.3.4, and necessarily imply the failures are independent (e.g., common cause failures are not likely) (SNL 2007f, Section 6.5.1). Details of the technical bases for the probability estimates, including the parameters and data used, and their associated uncertainties, are described in Section 2.3.6.8.4.

2.2.2.4 Human Intrusion
[NUREG-1804, Section 2.2.1.2.2.3: AC 1(1)]

2.2.2.4.1 Definition of Human Intrusion Event

The Human Intrusion Event is defined by 10 CFR 63.322, which states in part: (a) there is a single human intrusion as a result of exploratory drilling for groundwater; (b) the intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository; and (c) the drillers use the common techniques and practices that are currently employed in exploratory drilling for groundwater in the region surrounding Yucca Mountain. Table 2.2-6 summarizes the included Human Intrusion related FEPs.

2.2.2.4.2 Probability of Human Intrusion Event

As specified by 10 CFR 63.102(k), the human intrusion scenario is conducted as a separate analysis. The probability of the initiating event is not specified.

2.2.3 General References

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Table 2.2-1. List of Potentially Relevant Features, Events, and Processes

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
0.1.02.00.0A	Timescales of concern	Included	System	Characteristics
0.1.03.00.0A	Spatial domain of concern	Included	System	Characteristics
0.1.09.00.0A	Regulatory requirements and exclusions	Included	System	Characteristics
0.1.10.00.0A	Model and data issues	Included	System	Characteristics
1.1.01.01.0A	Open site investigation boreholes	Excluded	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
1.1.01.01.0B	Influx through holes drilled in drift wall or crown	Excluded	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
1.1.02.00.0A	Chemical effects of excavation and construction in EBS	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
1.1.02.00.0B	Mechanical effects of excavation and construction in EBS	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
1.1.02.01.0A	Site flooding (during construction and operation)	Excluded	Emplacement Drift	Hydrologic and Thermal-Hydrologic
1.1.02.02.0A	Preclosure ventilation	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic
1.1.02.03.0A	Undesirable materials left	Excluded	Emplacement Drift	Characteristics
1.1.03.01.0A	Error in waste emplacement	Excluded	Emplacement Drift	Characteristics
1.1.03.01.0B	Error in backfill emplacement	Excluded	Backfill/Seals	Characteristics
1.1.04.01.0A	Incomplete closure	Excluded	System	Characteristics
1.1.05.00.0A	Records and markers for the repository	Excluded	System	Human Intrusion
1.1.07.00.0A	Repository design	Included	System	Characteristics

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
1.1.08.00.0A	Inadequate quality control and deviations from design	Excluded	System	Characteristics
1.1.09.00.0A	Schedule and planning	Included	System	Characteristics
1.1.10.00.0A	Administrative control of the repository site	Excluded	System	Human Intrusion
1.1.11.00.0A	Monitoring of the repository	Excluded	System	Characteristics
1.1.12.01.0A	Accidents and unplanned events during construction and operation	Excluded	System	Characteristics
1.1.13.00.0A	Retrievability	Included	System	Characteristics
1.2.01.01.0A	Tectonic activity—large scale	Excluded	System	Characteristics
1.2.02.01.0A	Fractures	Included	Saturated Zone	Characteristics
1.2.02.01.0A	Fractures	Included	Topography and Surficial Soils	Characteristics
1.2.02.01.0A	Fractures	Included	Unsaturated Zone Above the Repository	Characteristics
1.2.02.01.0A	Fractures	Included	Unsaturated Zone Below the Repository	Characteristics
1.2.02.02.0A	Faults	Included	Saturated Zone	Characteristics
1.2.02.02.0A	Faults	Included	Unsaturated Zone Above the Repository	Characteristics
1.2.02.02.0A	Faults	Included	Unsaturated Zone Below the Repository	Characteristics
1.2.02.03.0A	Fault displacement damages EBS components	Included	Cladding	Seismic
1.2.02.03.0A	Fault displacement damages EBS components	Included	Invert	Seismic
1.2.02.03.0A	Fault displacement damages EBS components	Included	Waste Form and Waste Package Internals	Seismic
1.2.02.03.0A	Fault displacement damages EBS components	Included	Waste Package	Seismic
1.2.02.03.0A	Fault displacement damages EBS components	Included	Waste Package Pallet	Seismic

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
1.2.02.03.0A	Fault displacement damages EBS components	Included	Drip Shield	Seismic
1.2.02.03.0A	Fault displacement damages EBS components	Included	Emplacement Drift	Seismic
1.2.03.02.0A	Seismic ground motion damages EBS components	Included	Cladding	Seismic
1.2.03.02.0A	Seismic ground motion damages EBS components	Included	Drip Shield	Seismic
1.2.03.02.0A	Seismic ground motion damages EBS components	Included	Emplacement Drift	Seismic
1.2.03.02.0A	Seismic ground motion damages EBS components	Included	Invert	Seismic
1.2.03.02.0A	Seismic ground motion damages EBS components	Included	Waste Form and Waste Package Internals	Seismic
1.2.03.02.0A	Seismic ground motion damages EBS components	Included	Waste Package	Seismic
1.2.03.02.0A	Seismic ground motion damages EBS components	Included	Waste Package Pallet	Seismic
1.2.03.02.0B	Seismic-induced rockfall damages EBS components	Excluded	Emplacement Drift	Seismic
1.2.03.02.0B	Seismic-induced rockfall damages EBS components	Excluded	Waste Package	Seismic
1.2.03.02.0B	Seismic-induced rockfall damages EBS components	Excluded	Drip Shield	Seismic
1.2.03.02.0B	Seismic-induced rockfall damages EBS components	Excluded	Waste Form and Waste Package Internals	Seismic
1.2.03.02.0B	Seismic-induced rockfall damages EBS components	Excluded	Cladding	Seismic
1.2.03.02.0B	Seismic-induced rockfall damages EBS components	Excluded	Invert	Seismic
1.2.03.02.0B	Seismic-induced rockfall damages EBS components	Excluded	Waste Package Pallet	Seismic
1.2.03.02.0C	Seismic-induced drift collapse damages EBS components	Included	Emplacement Drift	Seismic
1.2.03.02.0C	Seismic-induced drift collapse damages EBS components	Included	Waste Package	Seismic
1.2.03.02.0C	Seismic-induced drift collapse damages EBS components	Included	Drip Shield	Seismic
1.2.03.02.0C	Seismic-induced drift collapse damages EBS components	Included	Waste Form and Waste Package Internals	Seismic

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
1.2.03.02.0C	Seismic-induced drift collapse damages EBS components	Included	Cladding	Seismic
1.2.03.02.0C	Seismic-induced drift collapse damages EBS components	Included	Invert	Seismic
1.2.03.02.0C	Seismic-induced drift collapse damages EBS components	Included	Waste Package Pallet	Seismic
1.2.03.02.0D	Seismic-induced drift collapse alters in-drift thermal-hydrology	Included	Emplacement Drift	Seismic
1.2.03.02.0E	Seismic-induced drift collapse alters in-drift chemistry	Excluded	Emplacement Drift	Seismic
1.2.03.03.0A	Seismicity associated with igneous activity	Included	Emplacement Drift	Seismic
1.2.04.02.0A	Igneous activity changes rock properties	Excluded	Saturated Zone	Igneous
1.2.04.02.0A	Igneous activity changes rock properties	Excluded	Unsaturated Zone Below the Repository	Igneous
1.2.04.02.0A	Igneous activity changes rock properties	Excluded	Unsaturated Zone Above the Repository	Igneous
1.2.04.03.0A	Igneous intrusion into repository	Included	Emplacement Drift	Igneous
1.2.04.04.0A	Igneous intrusion interacts with EBS components	Included	Emplacement Drift	Igneous
1.2.04.04.0A	Igneous intrusion interacts with EBS components	Included	Waste Package	Igneous
1.2.04.04.0A	Igneous intrusion interacts with EBS components	Included	Drip Shield	Igneous
1.2.04.04.0A	Igneous intrusion interacts with EBS components	Included	Waste Form and Waste Package Internals	Igneous
1.2.04.04.0A	Igneous intrusion interacts with EBS components	Included	Cladding	Igneous
1.2.04.04.0A	Igneous intrusion interacts with EBS components	Included	Invert	Igneous
1.2.04.04.0A	Igneous intrusion interacts with EBS components	Included	Waste Package Pallet	Igneous
1.2.04.04.0B	Chemical effects of magma and magmatic volatiles	Included	Emplacement Drift	Igneous
1.2.04.05.0A	Magma or pyroclastic base surge transports waste	Excluded	Emplacement Drift	Igneous
1.2.04.06.0A	Eruptive conduit to surface intersects repository	Included	Emplacement Drift	Igneous

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
1.2.04.07.0A	Ashfall	Included	Biosphere	Igneous
1.2.04.07.0B	Ash redistribution in groundwater	Excluded	Saturated Zone	Igneous
1.2.04.07.0C	Ash redistribution via soil and sediment transport	Included	Biosphere	Igneous
1.2.05.00.0A	Metamorphism	Excluded	System	Characteristics
1.2.06.00.0A	Hydrothermal activity	Excluded	Unsaturated Zone Above the Repository	Igneous
1.2.06.00.0A	Hydrothermal activity	Excluded	Unsaturated Zone Below the Repository	Igneous
1.2.06.00.0A	Hydrothermal activity	Excluded	Saturated Zone	Igneous
1.2.07.01.0A	Erosion/denudation	Excluded	Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic
1.2.07.02.0A	Deposition	Excluded	Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic
1.2.08.00.0A	Diagenesis	Excluded	System	Characteristics
1.2.09.00.0A	Salt diapirism and dissolution	Excluded	System	Characteristics
1.2.09.01.0A	Diapirism	Excluded	System	Characteristics
1.2.09.02.0A	Large-scale dissolution	Excluded	Saturated Zone	Chemical and Thermal-Chemical
1.2.10.01.0A	Hydrologic response to seismic activity	Excluded	Unsaturated Zone Above the Repository	Seismic
1.2.10.01.0A	Hydrologic response to seismic activity	Excluded	Unsaturated Zone Below the Repository	Seismic
1.2.10.01.0A	Hydrologic response to seismic activity	Excluded	Saturated Zone	Seismic
1.2.10.02.0A	Hydrologic response to igneous activity	Excluded	Unsaturated Zone Above the Repository	Igneous
1.2.10.02.0A	Hydrologic response to igneous activity	Excluded	Unsaturated Zone Below the Repository	Igneous

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
1.2.10.02.0A	Hydrologic response to igneous activity	Excluded	Saturated Zone	Igneous
1.3.01.00.0A	Climate change	Included	Saturated Zone	Hydrologic and Thermal-Hydrologic
1.3.01.00.0A	Climate change	Included	Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic
1.3.01.00.0A	Climate change	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
1.3.01.00.0A	Climate change	Included	Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic
1.3.04.00.0A	Periglacial effects	Excluded	System	Characteristics
1.3.05.00.0A	Glacial and ice sheet effect	Excluded	System	Characteristics
1.3.07.01.0A	Water table decline	Excluded	Saturated Zone	Hydrologic and Thermal-Hydrologic
1.3.07.02.0A	Water table rise affects SZ	Included	Saturated Zone	Hydrologic and Thermal-Hydrologic
1.3.07.02.0B	Water table rise affects UZ	Included	Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic
1.4.01.00.0A	Human influences on climate	Excluded	Biosphere	Characteristics
1.4.01.01.0A	Climate modification increases recharge	Included	Saturated Zone	Hydrologic and Thermal-Hydrologic
1.4.01.01.0A	Climate modification increases recharge	Included	Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic
1.4.01.01.0A	Climate modification increases recharge	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
1.4.01.01.0A	Climate modification increases recharge	Included	Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic
1.4.01.02.0A	Greenhouse gas effects	Excluded	Biosphere	Characteristics
1.4.01.03.0A	Acid rain	Excluded	Biosphere	Characteristics
1.4.01.04.0A	Ozone layer failure	Excluded	Biosphere	Characteristics
1.4.02.01.0A	Deliberate human intrusion	Excluded	System	Human Intrusion
1.4.02.02.0A	Inadvertent human intrusion	Included	System	Human Intrusion
1.4.02.03.0A	Igneous event precedes human intrusion	Excluded	System	Human Intrusion
1.4.02.04.0A	Seismic event precedes human intrusion	Excluded	System	Human Intrusion
1.4.03.00.0A	Unintrusive site investigation	Excluded	System	Human Intrusion
1.4.04.00.0A	Drilling activities (human intrusion)	Included	System	Human Intrusion
1.4.04.01.0A	Effects of drilling intrusion	Included	System	Human Intrusion
1.4.05.00.0A	Mining and other underground activities (human intrusion)	Excluded	System	Human Intrusion
1.4.06.01.0A	Altered soil or surface water chemistry	Excluded	Unsaturated Zone Above the Repository	Chemical and Thermal-Chemical
1.4.07.01.0A	Water management activities	Included	Biosphere	Characteristics
1.4.07.02.0A	Wells	Included	Saturated Zone	Transport
1.4.07.03.0A	Recycling of accumulated radionuclides from soils to groundwater	Excluded	Biosphere	Transport
1.4.08.00.0A	Social and institutional developments	Excluded	Biosphere	Characteristics
1.4.09.00.0A	Technological developments	Excluded	Biosphere	Characteristics

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
1.4.11.00.0A	Explosions and crashes (human activities)	Excluded	System	Human Intrusion
1.5.01.01.0A	Meteorite impact	Excluded	System	Characteristics
1.5.01.02.0A	Extraterrestrial events	Excluded	System	Characteristics
1.5.02.00.0A	Species evolution	Excluded	Biosphere	Characteristics
1.5.03.01.0A	Changes in the earth's magnetic field	Excluded	System	Characteristics
1.5.03.02.0A	Earth tides	Excluded	System	Characteristics
2.1.01.01.0A	Waste inventory	Included	Waste Form and Waste Package Internals	Characteristics
2.1.01.02.0A	Interactions between co-located waste	Excluded	Waste Form and Waste Package Internals	Characteristics
2.1.01.02.0B	Interactions between co-disposed waste	Included	Waste Form and Waste Package Internals	Characteristics
2.1.01.03.0A	Heterogeneity of waste inventory	Included	Waste Form and Waste Package Internals	Characteristics
2.1.01.04.0A	Repository-scale spatial heterogeneity of emplaced waste	Included	Waste Form and Waste Package Internals	Characteristics
2.1.01.04.0A	Repository-scale spatial heterogeneity of emplaced waste	Included	Emplacement Drift	Characteristics
2.1.02.01.0A	DSNF degradation (alteration, dissolution, and radionuclide release)	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.02.02.0A	CSNF degradation (alteration, dissolution, and radionuclide release)	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.02.03.0A	HLW glass degradation (alteration, dissolution, and radionuclide release)	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.02.04.0A	Alpha recoil enhances dissolution	Excluded	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.02.05.0A	HLW glass cracking	Included	Waste Form and Waste Package Internals	Mechanical and Thermal-Mechanical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.02.06.0A	HLW glass recrystallization	Excluded	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.02.07.0A	Radionuclide release from gap and grain boundaries	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.02.08.0A	Pyrophoricity from DSNF	Excluded	Waste Form and Waste Package Internals	Characteristics
2.1.02.09.0A	Chemical effects of void space in waste package	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.02.10.0A	Organic/cellulosic materials in waste	Excluded	Waste Form and Waste Package Internals	Characteristics
2.1.02.11.0A	Degradation of cladding from waterlogged rods	Excluded	Cladding	Mechanical and Thermal-Mechanical
2.1.02.12.0A	Degradation of cladding prior to disposal	Included	Cladding	Mechanical and Thermal-Mechanical
2.1.02.13.0A	General corrosion of cladding	Excluded	Cladding	Chemical and Thermal-Chemical
2.1.02.14.0A	Microbially influenced corrosion (MIC) of cladding	Excluded	Cladding	Chemical and Thermal-Chemical
2.1.02.15.0A	Localized (radiolysis enhanced) corrosion of cladding	Excluded	Cladding	Chemical and Thermal-Chemical
2.1.02.16.0A	Localized (pitting) corrosion of cladding	Excluded	Cladding	Chemical and Thermal-Chemical
2.1.02.17.0A	Localized (crevice) corrosion of cladding	Excluded	Cladding	Chemical and Thermal-Chemical
2.1.02.18.0A	Enhanced corrosion of cladding from dissolved silica	Excluded	Cladding	Chemical and Thermal-Chemical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.02.19.0A	Creep rupture of cladding	Excluded	Cladding	Mechanical and Thermal-Mechanical
2.1.02.20.0A	Internal pressurization of cladding	Excluded	Cladding	Mechanical and Thermal-Mechanical
2.1.02.21.0A	Stress corrosion cracking (SCC) of cladding	Excluded	Cladding	Chemical and Thermal-Chemical
2.1.02.22.0A	Hydride cracking of cladding	Excluded	Cladding	Chemical and Thermal-Chemical
2.1.02.23.0A	Cladding unzipping	Included	Cladding	Mechanical and Thermal-Mechanical
2.1.02.24.0A	Mechanical impact on cladding	Excluded	Cladding	Mechanical and Thermal-Mechanical
2.1.02.25.0A	DSNF cladding	Excluded	Cladding	Mechanical and Thermal-Mechanical
2.1.02.25.0B	Naval SNF Cladding	Included	Cladding	Mechanical and Thermal-Mechanical
2.1.02.26.0A	Diffusion-controlled cavity growth in cladding	Excluded	Cladding	Mechanical and Thermal-Mechanical
2.1.02.27.0A	Localized (fluoride enhanced) corrosion of cladding	Excluded	Cladding	Chemical and Thermal-Chemical
2.1.02.28.0A	Grouping of DSNF waste types into categories	Included	Waste Form and Waste Package Internals	Characteristics
2.1.02.29.0A	Flammable gas generation from DSNF	Excluded	Waste Form and Waste Package Internals	Characteristics
2.1.03.01.0A	General corrosion of waste packages	Included	Waste Package	Chemical and Thermal-Chemical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.03.01.0B	General corrosion of drip shields	Included	Drip Shield	Chemical and Thermal-Chemical
2.1.03.02.0A	Stress corrosion cracking (SCC) of waste packages	Included	Waste Package	Chemical and Thermal-Chemical
2.1.03.02.0B	Stress corrosion cracking (SCC) of drip shields	Excluded	Drip Shield	Chemical and Thermal-Chemical
2.1.03.03.0A	Localized corrosion of waste packages	Included	Waste Package	Chemical and Thermal-Chemical
2.1.03.03.0B	Localized corrosion of drip shields	Excluded	Drip Shield	Chemical and Thermal-Chemical
2.1.03.04.0A	Hydride cracking of waste packages	Excluded	Waste Package	Chemical and Thermal-Chemical
2.1.03.04.0B	Hydride cracking of drip shields	Excluded	Drip Shield	Chemical and Thermal-Chemical
2.1.03.05.0A	Microbially influenced corrosion (MIC) of waste packages	Included	Waste Package	Chemical and Thermal-Chemical
2.1.03.05.0B	Microbially influenced corrosion (MIC) of drip shields	Excluded	Drip Shield	Chemical and Thermal-Chemical
2.1.03.06.0A	Internal corrosion of waste packages prior to breach	Excluded	Waste Package	Chemical and Thermal-Chemical
2.1.03.06.0A	Internal corrosion of waste packages prior to breach	Excluded	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.03.07.0A	Mechanical impact on waste package	Excluded	Waste Package	Mechanical
2.1.03.07.0B	Mechanical impact on drip shield	Excluded	Drip Shield	Mechanical
2.1.03.08.0A	Early failure of waste packages	Included	Waste Package	Early Failure

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.03.08.0B	Early failure of drip shields	Included	Drip Shield	Early Failure
2.1.03.09.0A	Copper corrosion in EBS	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.1.03.10.0A	Advection of liquids and solids through cracks in the waste package	Excluded	Waste Package	Hydrologic and Thermal-Hydrologic
2.1.03.10.0B	Advection of liquids and solids through cracks in the drip shield	Excluded	Drip Shield	Hydrologic and Thermal-Hydrologic
2.1.03.11.0A	Physical form of waste package and drip shield	Included	Waste Package	Characteristics
2.1.03.11.0A	Physical form of waste package and drip shield	Included	Drip Shield	Characteristics
2.1.04.01.0A	Flow in the backfill	Excluded	Backfill/Seals	Hydrologic and Thermal-Hydrologic
2.1.04.02.0A	Chemical properties and evolution of backfill	Excluded	Backfill/Seals	Chemical and Thermal-Chemical
2.1.04.03.0A	Erosion or dissolution of backfill	Excluded	Backfill/Seals	Mechanical and Thermal-Mechanical
2.1.04.04.0A	Thermal-mechanical effects of backfill	Excluded	Backfill/Seals	Mechanical and Thermal-Mechanical
2.1.04.05.0A	Thermal-mechanical properties and evolution of backfill	Excluded	Backfill/Seals	Mechanical and Thermal-Mechanical
2.1.04.09.0A	Radionuclide transport in backfill	Excluded	Backfill/Seals	Transport
2.1.05.01.0A	Flow through seals (access ramps and ventilation shafts)	Excluded	Backfill/Seals	Hydrologic and Thermal-Hydrologic
2.1.05.02.0A	Radionuclide transport through seals	Excluded	Backfill/Seals	Transport

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.05.03.0A	Degradation of seals	Excluded	Backfill/Seals	Mechanical and Thermal-Mechanical
2.1.06.01.0A	Chemical effects of rock reinforcement and cementitious materials in EBS	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.1.06.02.0A	Mechanical effects of rock reinforcement materials in EBS	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
2.1.06.04.0A	Flow through rock reinforcement materials in EBS	Excluded	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.06.05.0A	Mechanical degradation of emplacement pallet	Excluded	Waste Package Pallet	Mechanical and Thermal-Mechanical
2.1.06.05.0B	Mechanical degradation of invert	Excluded	Invert	Mechanical and Thermal-Mechanical
2.1.06.05.0C	Chemical degradation of emplacement pallet	Included	Waste Package Pallet	Chemical and Thermal-Chemical
2.1.06.05.0D	Chemical degradation of invert	Excluded	Invert	Chemical and Thermal-Chemical
2.1.06.06.0A	Effects of drip shield on flow	Included	Drip Shield	Hydrologic and Thermal-Hydrologic
2.1.06.06.0B	Oxygen embrittlement of drip shields	Excluded	Drip Shield	Chemical and Thermal-Chemical
2.1.06.07.0A	Chemical effects at EBS component interfaces	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.1.06.07.0A	Chemical effects at EBS component interfaces	Excluded	Drip Shield	Chemical and Thermal-Chemical
2.1.06.07.0A	Chemical effects at EBS component interfaces	Excluded	Waste Package Pallet	Chemical and Thermal-Chemical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded	Drip Shield	Mechanical and Thermal-Mechanical
2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded	Waste Package	Mechanical and Thermal-Mechanical
2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded	Waste Package Pallet	Mechanical and Thermal-Mechanical
2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded	Invert	Mechanical and Thermal-Mechanical
2.1.07.01.0A	Rockfall	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
2.1.07.01.0A	Rockfall	Excluded	Drip Shield	Mechanical and Thermal-Mechanical
2.1.07.01.0A	Rockfall	Excluded	Waste Package	Mechanical and Thermal-Mechanical
2.1.07.02.0A	Drift collapse	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
2.1.07.04.0A	Hydrostatic pressure on waste package	Excluded	Waste Package	Mechanical and Thermal-Mechanical
2.1.07.04.0B	Hydrostatic pressure on drip shield	Excluded	Drip Shield	Mechanical and Thermal-Mechanical
2.1.07.05.0A	Creep of metallic materials in the waste package	Excluded	Waste Package	Mechanical and Thermal-Mechanical
2.1.07.05.0B	Creep of metallic materials in the drip shield	Excluded	Drip Shield	Mechanical and Thermal-Mechanical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.07.06.0A	Floor buckling	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
2.1.08.01.0A	Water influx at the repository	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.1.08.01.0B	Effects of rapid influx into the repository	Excluded	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.1.08.01.0B	Effects of rapid influx into the repository	Excluded	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.08.02.0A	Enhanced influx at the repository	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.1.08.03.0A	Repository dry-out due to waste heat	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.1.08.03.0A	Repository dry-out due to waste heat	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.08.04.0A	Condensation forms on roofs of drifts (drift-scale cold traps)	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.08.04.0B	Condensation forms at repository edges (repository-scale cold traps)	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.08.05.0A	Flow through invert	Included	Invert	Hydrologic and Thermal-Hydrologic
2.1.08.06.0A	Capillary effects (wicking) in EBS	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.08.06.0A	Capillary effects (wicking) in EBS	Included	Invert	Hydrologic and Thermal-Hydrologic
2.1.08.07.0A	Unsaturated flow in the EBS	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.08.07.0A	Unsaturated flow in the EBS	Included	Invert	Hydrologic and Thermal-Hydrologic
2.1.08.09.0A	Saturated flow in the EBS	Excluded	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.08.11.0A	Repository resaturation due to waste cooling	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.1.08.12.0A	Induced hydrologic changes in invert	Excluded	Invert	Hydrologic and Thermal-Hydrologic
2.1.08.14.0A	Condensation on underside of drip shield	Excluded	Drip Shield	Hydrologic and Thermal-Hydrologic
2.1.08.15.0A	Consolidation of EBS components	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
2.1.08.15.0A	Consolidation of EBS components	Excluded	Waste Package	Mechanical and Thermal-Mechanical
2.1.08.15.0A	Consolidation of EBS components	Excluded	Drip Shield	Mechanical and Thermal-Mechanical
2.1.08.15.0A	Consolidation of EBS components	Excluded	Waste Form and Waste Package Internals	Mechanical and Thermal-Mechanical
2.1.08.15.0A	Consolidation of EBS components	Excluded	Cladding	Mechanical and Thermal-Mechanical
2.1.08.15.0A	Consolidation of EBS components	Excluded	Invert	Mechanical and Thermal-Mechanical
2.1.08.15.0A	Consolidation of EBS components	Excluded	Waste Package Pallet	Mechanical and Thermal-Mechanical
2.1.09.01.0A	Chemical characteristics of water in drifts	Included	Emplacement Drift	Characteristics

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.09.01.0A	Chemical characteristics of water in drifts	Included	Invert	Characteristics
2.1.09.01.0B	Chemical characteristics of water in waste package	Included	Waste Form and Waste Package Internals	Characteristics
2.1.09.02.0A	Chemical interaction with corrosion products	Included	Emplacement Drift	Chemical and Thermal-Chemical
2.1.09.02.0A	Chemical interaction with corrosion products	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.09.03.0A	Volume increase of corrosion products impacts cladding	Excluded	Cladding	Mechanical and Thermal-Mechanical
2.1.09.03.0B	Volume increase of corrosion products impacts waste package	Excluded	Waste Package	Mechanical and Thermal-Mechanical
2.1.09.03.0C	Volume increase of corrosion products impacts other EBS components	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
2.1.09.04.0A	Radionuclide solubility, solubility limits, and speciation in the waste form and EBS	Included	Invert	Transport
2.1.09.04.0A	Radionuclide solubility, solubility limits, and speciation in the waste form and EBS	Included	Waste Form and Waste Package Internals	Transport
2.1.09.05.0A	Sorption of dissolved radionuclides in EBS	Included	Invert	Transport
2.1.09.05.0A	Sorption of dissolved radionuclides in EBS	Included	Waste Form and Waste Package Internals	Transport
2.1.09.06.0A	Reduction-oxidation potential in waste package	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.09.06.0B	Reduction-oxidation potential in drifts	Included	Invert	Chemical and Thermal-Chemical
2.1.09.07.0A	Reaction kinetics in waste package	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.09.07.0B	Reaction kinetics in drifts	Included	Invert	Chemical and Thermal-Chemical
2.1.09.08.0A	Diffusion of dissolved radionuclides in EBS	Included	Invert	Transport
2.1.09.08.0A	Diffusion of dissolved radionuclides in EBS	Included	Waste Form and Waste Package Internals	Transport
2.1.09.08.0B	Advection of dissolved radionuclides in EBS	Included	Invert	Transport
2.1.09.08.0B	Advection of dissolved radionuclides in EBS	Included	Waste Form and Waste Package Internals	Transport
2.1.09.09.0A	Electrochemical effects in EBS	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.1.09.10.0A	Secondary phase effects on dissolved radionuclide concentrations	Excluded	Waste Form and Waste Package Internals	Transport
2.1.09.11.0A	Chemical effects of waste–rock contact	Excluded	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.09.12.0A	Rind (chemically altered zone) forms in the near-field	Excluded	Unsaturated Zone Above the Repository	Chemical and Thermal-Chemical
2.1.09.12.0A	Rind (chemically altered zone) forms in the near-field	Excluded	Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical
2.1.09.13.0A	Complexation in EBS	Excluded	Invert	Microbiological
2.1.09.15.0A	Formation of true (intrinsic) colloids in EBS	Excluded	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.09.16.0A	Formation of pseudo-colloids (natural) in EBS	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.09.17.0A	Formation of pseudo-colloids (corrosion product) in EBS	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.09.18.0A	Formation of microbial colloids in EBS	Excluded	Waste Form and Waste Package Internals	Microbiological

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.09.19.0A	Sorption of colloids in EBS	Excluded	Invert	Transport
2.1.09.19.0A	Sorption of colloids in EBS	Excluded	Waste Form and Waste Package Internals	Transport
2.1.09.19.0B	Advection of colloids in EBS	Included	Invert	Transport
2.1.09.19.0B	Advection of colloids in EBS	Included	Waste Form and Waste Package Internals	Transport
2.1.09.20.0A	Filtration of colloids in EBS	Excluded	Invert	Transport
2.1.09.20.0A	Filtration of colloids in EBS	Excluded	Waste Form and Waste Package Internals	Transport
2.1.09.21.0A	Transport of particles larger than colloids in EBS	Excluded	Invert	Transport
2.1.09.21.0B	Transport of particles larger than colloids in the SZ	Excluded	Saturated Zone	Transport
2.1.09.21.0C	Transport of particles larger than colloids in the UZ	Excluded	Unsaturated Zone Below the Repository	Transport
2.1.09.22.0A	Sorption of colloids at air–water interface	Excluded	Invert	Transport
2.1.09.23.0A	Stability of colloids in EBS	Included	Invert	Transport
2.1.09.23.0A	Stability of colloids in EBS	Included	Waste Form and Waste Package Internals	Transport
2.1.09.24.0A	Diffusion of colloids in EBS	Included	Waste Form and Waste Package Internals	Transport
2.1.09.24.0A	Diffusion of colloids in EBS	Included	Invert	Transport
2.1.09.25.0A	Formation of colloids (waste form) by co-precipitation in EBS	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.09.26.0A	Gravitational settling of colloids in EBS	Excluded	Invert	Transport
2.1.09.27.0A	Coupled effects on radionuclide transport in EBS	Excluded	Invert	Transport
2.1.09.28.0A	Localized corrosion on waste package outer surface due to deliquescence	Excluded	Waste Package	Chemical and Thermal-Chemical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.09.28.0B	Localized corrosion on drip shield surfaces due to deliquescence	Excluded	Drip Shield	Chemical and Thermal-Chemical
2.1.10.01.0A	Microbial activity in EBS	Excluded	Emplacement Drift	Microbiological
2.1.11.01.0A	Heat generation in EBS	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.11.02.0A	Nonuniform heat distribution in EBS	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.11.03.0A	Exothermic reactions in the EBS	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.1.11.03.0A	Exothermic reactions in the EBS	Excluded	Waste Package	Chemical and Thermal-Chemical
2.1.11.05.0A	Thermal expansion/stress of in-package EBS components	Excluded	Waste Form and Waste Package Internals	Mechanical and Thermal-Mechanical
2.1.11.06.0A	Thermal sensitization of waste packages	Excluded	Waste Package	Chemical and Thermal-Chemical
2.1.11.06.0B	Thermal sensitization of drip shields	Excluded	Drip Shield	Chemical and Thermal-Chemical
2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded	Drip Shield	Mechanical and Thermal-Mechanical
2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded	Waste Package	Mechanical and Thermal-Mechanical
2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded	Waste Package Pallet	Mechanical and Thermal-Mechanical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded	Invert	Mechanical and Thermal-Mechanical
2.1.11.08.0A	Thermal effects on chemistry and microbial activity in the EBS	Included	Emplacement Drift	Chemical and Thermal-Chemical
2.1.11.09.0A	Thermal effects on flow in the EBS	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.11.09.0B	Thermally driven flow (convection) in waste packages	Excluded	Waste Form and Waste Package Internals	Hydrologic and Thermal-Hydrologic
2.1.11.09.0C	Thermally driven flow (convection) in drifts	Included	Emplacement Drift	Hydrologic and Thermal-Hydrologic
2.1.11.10.0A	Thermal effects on transport in EBS	Excluded	Invert	Transport
2.1.12.01.0A	Gas generation (repository pressurization)	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.1.12.02.0A	Gas generation (He) from waste form decay	Excluded	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.1.12.03.0A	Gas generation (H_2) from waste package corrosion	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.1.12.03.0A	Gas generation (H_2) from waste package corrosion	Excluded	Waste Package	Chemical and Thermal-Chemical
2.1.12.04.0A	Gas generation (CO_2, CH_4, H_2S) from microbial degradation	Excluded	Emplacement Drift	Microbiological
2.1.12.06.0A	Gas transport in EBS	Excluded	Invert	Transport
2.1.12.07.0A	Effects of radioactive gases in EBS	Excluded	Invert	Transport
2.1.12.08.0A	Gas explosions in EBS	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.13.01.0A	Radiolysis	Excluded	Emplacement Drift	Radiological
2.1.13.01.0A	Radiolysis	Excluded	Waste Package	Radiological
2.1.13.02.0A	Radiation damage in EBS	Excluded	Emplacement Drift	Radiological
2.1.13.02.0A	Radiation damage in EBS	Excluded	Waste Package	Radiological
2.1.13.02.0A	Radiation damage in EBS	Excluded	Drip Shield	Radiological
2.1.13.03.0A	Radiological mutation of microbes	Excluded	Emplacement Drift	Radiological
2.1.14.15.0A	In-package criticality (intact configuration)	Excluded	Waste Package	Criticality
2.1.14.16.0A	In-package criticality (degraded configurations)	Excluded	Waste Package	Criticality
2.1.14.17.0A	Near-field criticality	Excluded	Invert	Criticality
2.1.14.18.0A	In-package criticality resulting from a seismic event (intact configuration)	Excluded	Waste Package	Criticality
2.1.14.19.0A	In-package criticality resulting from a seismic event (degraded configurations)	Excluded	Waste Package	Criticality
2.1.14.20.0A	Near-field criticality resulting from a seismic event	Excluded	Invert	Criticality
2.1.14.21.0A	In-package criticality resulting from rockfall (intact configuration)	Excluded	Waste Package	Criticality
2.1.14.22.0A	In-package criticality resulting from rockfall (degraded configurations)	Excluded	Waste Package	Criticality
2.1.14.23.0A	Near-field criticality resulting from rockfall	Excluded	Invert	Criticality
2.1.14.24.0A	In-package criticality resulting from an igneous event (intact configuration)	Excluded	Waste Package	Criticality
2.1.14.25.0A	In-package criticality resulting from an igneous event (degraded configurations)	Excluded	Waste Package	Criticality

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.1.14.26.0A	Near-field criticality resulting from an igneous event	Excluded	Invert	Criticality
2.2.01.01.0A	Mechanical effects of excavation and construction in the near-field	Included	Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical
2.2.01.01.0B	Chemical effects of excavation and construction in the near-field	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.2.01.01.0B	Chemical effects of excavation and construction in the near-field	Excluded	Unsaturated Zone Above the Repository	Chemical and Thermal-Chemical
2.2.01.02.0A	Thermally induced stress changes in the near-field	Excluded	Emplacement Drift	Mechanical and Thermal-Mechanical
2.2.01.02.0A	Thermally induced stress changes in the near-field	Excluded	Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical
2.2.01.02.0B	Chemical changes in the near-field from backfill	Excluded	Backfill/Seals	Chemical and Thermal-Chemical
2.2.01.02.0B	Chemical changes in the near-field from backfill	Excluded	Unsaturated Zone Above the Repository	Chemical and Thermal-Chemical
2.2.01.02.0B	Chemical changes in the near-field from backfill	Excluded	Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical
2.2.01.03.0A	Changes in fluid saturations in the excavation disturbed zone	Excluded	Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic
2.2.01.04.0A	Radionuclide solubility in the excavation disturbed zone	Excluded	Unsaturated Zone Below the Repository	Transport
2.2.01.05.0A	Radionuclide transport in the excavation disturbed zone	Excluded	Unsaturated Zone Below the Repository	Transport
2.2.03.01.0A	Stratigraphy	Included	Saturated Zone	Characteristics
2.2.03.01.0A	Stratigraphy	Included	Unsaturated Zone Above the Repository	Characteristics
2.2.03.01.0A	Stratigraphy	Included	Unsaturated Zone Below the Repository	Characteristics

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.2.03.02.0A	Rock properties of host rock and other units	Included	Saturated Zone	Characteristics
2.2.03.02.0A	Rock properties of host rock and other units	Included	Topography and Surficial Soils	Characteristics
2.2.03.02.0A	Rock properties of host rock and other units	Included	Unsaturated Zone Above the Repository	Characteristics
2.2.03.02.0A	Rock properties of host rock and other units	Included	Unsaturated Zone Below the Repository	Characteristics
2.2.06.01.0A	Seismic activity changes porosity and permeability of rock	Excluded	Unsaturated Zone Above the Repository	Seismic
2.2.06.01.0A	Seismic activity changes porosity and permeability of rock	Excluded	Unsaturated Zone Below the Repository	Seismic
2.2.06.01.0A	Seismic activity changes porosity and permeability of rock	Excluded	Saturated Zone	Seismic
2.2.06.02.0A	Seismic activity changes porosity and permeability of faults	Excluded	Unsaturated Zone Above Repository	Seismic
2.2.06.02.0A	Seismic activity changes porosity and permeability of faults	Excluded	Unsaturated Zone Below Repository	Seismic
2.2.06.02.0A	Seismic activity changes porosity and permeability of faults	Excluded	Saturated Zone	Seismic
2.2.06.02.0B	Seismic activity changes porosity and permeability of fractures	Excluded	Unsaturated Zone Above Repository	Seismic
2.2.06.02.0B	Seismic activity changes porosity and permeability of fractures	Excluded	Unsaturated Zone Below Repository	Seismic
2.2.06.02.0B	Seismic activity changes porosity and permeability of fractures	Excluded	Saturated Zone	Seismic
2.2.06.03.0A	Seismic activity alters perched water zones	Excluded	Unsaturated Zone Above Repository	Seismic
2.2.06.03.0A	Seismic activity alters perched water zones	Excluded	Unsaturated Zone Below Repository	Seismic
2.2.06.04.0A	Effects of subsidence	Excluded	Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical
2.2.06.04.0A	Effects of subsidence	Excluded	Topography and Surficial Soils	Mechanical and Thermal-Mechanical
2.2.06.05.0A	Salt creep	Excluded	System	Characteristics

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.2.07.01.0A	Locally saturated flow at bedrock/alluvium contact	Excluded	Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic
2.2.07.01.0A	Locally saturated flow at bedrock/alluvium contact	Excluded	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.02.0A	Unsaturated groundwater flow in the geosphere	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.02.0A	Unsaturated groundwater flow in the geosphere	Included	Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.03.0A	Capillary rise in the UZ	Included	Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.04.0A	Focusing of unsaturated flow (fingers, weeps)	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.05.0A	Flow in the UZ from episodic infiltration	Excluded	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.06.0A	Episodic or pulse release from repository	Excluded	Invert	Transport
2.2.07.06.0B	Long-term release of radionuclides from the repository	Included	Invert	Transport
2.2.07.06.0B	Long-term release of radionuclides from the repository	Included	Emplacement Drift	Transport
2.2.07.07.0A	Perched water develops	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.07.0A	Perched water develops	Included	Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.08.0A	Fracture flow in the UZ	Included	Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic
2.2.07.08.0A	Fracture flow in the UZ	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.2.07.08.0A	Fracture flow in the UZ	Included	Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.09.0A	Matrix imbibition in the UZ	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.09.0A	Matrix imbibition in the UZ	Included	Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.10.0A	Condensation zone forms around drifts	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.11.0A	Resaturation of geosphere dry-out zone	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.12.0A	Saturated groundwater flow in the geosphere	Included	Saturated Zone	Hydrologic and Thermal-Hydrologic
2.2.07.13.0A	Water-conducting features in the SZ	Included	Saturated Zone	Characteristics
2.2.07.14.0A	Chemically induced density effects on groundwater flow	Excluded	Saturated Zone	Characteristics
2.2.07.15.0A	Advection and dispersion in the SZ	Included	Saturated Zone	Transport
2.2.07.15.0B	Advection and dispersion in the UZ	Included	Unsaturated Zone Below the Repository	Transport
2.2.07.16.0A	Dilution of radionuclides in groundwater	Included	Saturated Zone	Transport
2.2.07.17.0A	Diffusion in the SZ	Included	Saturated Zone	Transport
2.2.07.18.0A	Film flow into the repository	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.19.0A	Lateral flow from Solitario Canyon Fault enters drifts	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.07.20.0A	Flow diversion around repository drifts	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.2.07.21.0A	Drift shadow forms below repository	Excluded	Unsaturated Zone Below the Repository	Transport
2.2.08.01.0A	Chemical characteristics of groundwater in the SZ	Included	Saturated Zone	Characteristics
2.2.08.01.0B	Chemical characteristics of groundwater in the UZ	Included	Unsaturated Zone Below the Repository	Characteristics
2.2.08.03.0A	Geochemical interactions and evolution in the SZ	Excluded	Saturated Zone	Chemical and Thermal-Chemical
2.2.08.03.0B	Geochemical interactions and evolution in the UZ	Excluded	Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical
2.2.08.03.0B	Geochemical interactions and evolution in the UZ	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.2.08.04.0A	Re-dissolution of precipitates directs more corrosive fluids to waste packages	Excluded	Emplacement Drift	Chemical and Thermal-Chemical
2.2.08.05.0A	Diffusion in the UZ	Excluded	Unsaturated Zone Below the Repository	Transport
2.2.08.06.0A	Complexation in the SZ	Included	Saturated Zone	Microbiological
2.2.08.06.0B	Complexation in the UZ	Included	Unsaturated Zone Below the Repository	Microbiological
2.2.08.07.0A	Radionuclide solubility limits in the SZ	Excluded	Saturated Zone	Transport
2.2.08.07.0B	Radionuclide solubility limits in the UZ	Excluded	Unsaturated Zone Below the Repository	Transport
2.2.08.07.0C	Radionuclide solubility limits in the biosphere	Excluded	Biosphere	Transport
2.2.08.08.0A	Matrix diffusion in the SZ	Included	Saturated Zone	Transport
2.2.08.08.0B	Matrix diffusion in the UZ	Included	Unsaturated Zone Below the Repository	Transport
2.2.08.09.0A	Sorption in the SZ	Included	Saturated Zone	Transport
2.2.08.09.0B	Sorption in the UZ	Included	Unsaturated Zone Below the Repository	Transport
2.2.08.10.0A	Colloidal transport in the SZ	Included	Saturated Zone	Transport

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.2.08.10.0B	Colloidal transport in the UZ	Included	Unsaturated Zone Below the Repository	Transport
2.2.08.11.0A	Groundwater discharge to surface within the reference biosphere	Excluded	Biosphere	Transport
2.2.08.12.0A	Chemistry of water flowing into the drift	Included	Emplacement Drift	Chemical and Thermal-Chemical
2.2.08.12.0B	Chemistry of water flowing into the waste package	Included	Waste Form and Waste Package Internals	Chemical and Thermal-Chemical
2.2.09.01.0A	Microbial activity in the SZ	Excluded	Saturated Zone	Microbiological
2.2.09.01.0B	Microbial activity in the UZ	Excluded	Unsaturated Zone Below the Repository	Microbiological
2.2.10.01.0A	Repository-induced thermal effects on flow in the UZ	Excluded	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.10.02.0A	Thermal convection cell develops in SZ	Excluded	Saturated Zone	Hydrologic and Thermal-Hydrologic
2.2.10.03.0A	Natural geothermal effects on flow in the SZ	Included	Saturated Zone	Hydrologic and Thermal-Hydrologic
2.2.10.03.0B	Natural geothermal effects on flow in the UZ	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.10.04.0A	Thermal-mechanical stresses alter characteristics of fractures near repository	Excluded	Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical
2.2.10.04.0A	Thermal-mechanical stresses alter characteristics of fractures near repository	Excluded	Unsaturated Zone Below the Repository	Mechanical and Thermal-Mechanical
2.2.10.04.0B	Thermal-mechanical stresses alter characteristics of faults near repository	Excluded	Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical
2.2.10.04.0B	Thermal-mechanical stresses alter characteristics of faults near repository	Excluded	Unsaturated Zone Below the Repository	Mechanical and Thermal-Mechanical

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.2.10.05.0A	Thermal-mechanical stresses alter characteristics of rocks above and below the repository	Excluded	Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical
2.2.10.05.0A	Thermal-mechanical stresses alter characteristics of rocks above and below the repository	Excluded	Unsaturated Zone Below the Repository	Mechanical and Thermal-Mechanical
2.2.10.06.0A	Thermal-chemical alteration in the UZ (solubility, speciation, phase changes, precipitation/dissolution)	Excluded	Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical
2.2.10.07.0A	Thermal-chemical alteration of the Calico Hills unit	Excluded	Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical
2.2.10.08.0A	Thermal-chemical alteration in the SZ (solubility, speciation, phase changes, precipitation/dissolution)	Excluded	Saturated Zone	Chemical and Thermal-Chemical
2.2.10.09.0A	Thermal-chemical alteration of the Topopah Spring basal vitrophyre	Excluded	Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical
2.2.10.10.0A	Two-phase buoyant flow/heat pipes	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.10.11.0A	Natural air flow in the UZ	Excluded	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.10.12.0A	Geosphere dry-out due to waste heat	Included	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic
2.2.10.13.0A	Repository-induced thermal effects on flow in the SZ	Excluded	Saturated Zone	Hydrologic and Thermal-Hydrologic
2.2.10.14.0A	Mineralogic dehydration reactions	Excluded	Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical
2.2.11.01.0A	Gas effects in the SZ	Excluded	Saturated Zone	Hydrologic and Thermal-Hydrologic
2.2.11.02.0A	Gas effects in the UZ	Excluded	Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.2.11.03.0A	Gas transport in geosphere	Excluded	Unsaturated Zone Below the Repository	Transport
2.2.12.00.0A	Undetected features in the UZ	Excluded	Unsaturated Zone Above the Repository	Characteristics
2.2.12.00.0A	Undetected features in the UZ	Excluded	Unsaturated Zone Below the Repository	Characteristics
2.2.12.00.0B	Undetected features in the SZ	Included	Saturated Zone	Characteristics
2.2.14.09.0A	Far-field criticality	Excluded	Unsaturated Zone Below the Repository	Criticality
2.2.14.10.0A	Far-field criticality resulting from a seismic event	Excluded	Unsaturated Zone Below the Repository	Criticality
2.2.14.11.0A	Far-field criticality resulting from rockfall	Excluded	Unsaturated Zone Below the Repository	Criticality
2.2.14.12.0A	Far-field criticality resulting from an igneous event	Excluded	Unsaturated Zone Below the Repository	Criticality
2.3.01.00.0A	Topography and morphology	Included	Topography and Surficial Soils	Characteristics
2.3.02.01.0A	Soil type	Included	Biosphere	Characteristics
2.3.02.02.0A	Radionuclide accumulation in soils	Included	Biosphere	Transport
2.3.02.03.0A	Soil and sediment transport in the biosphere	Included	Biosphere	Transport
2.3.04.01.0A	Surface water transport and mixing	Included	Biosphere	Transport
2.3.06.00.0A	Marine features	Excluded	System	Characteristics
2.3.09.01.0A	Animal burrowing/intrusion	Excluded	Biosphere	Transport
2.3.11.01.0A	Precipitation	Included	Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic
2.3.11.01.0A	Precipitation	Included	Biosphere	Hydrologic and Thermal-Hydrologic
2.3.11.02.0A	Surface runoff and evapotranspiration	Included	Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
2.3.11.03.0A	Infiltration and recharge	Included	Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic
2.3.11.04.0A	Groundwater discharge to surface outside the reference biosphere	Excluded	Biosphere	Transport
2.3.13.01.0A	Biosphere characteristics	Included	Biosphere	Characteristics
2.3.13.02.0A	Radionuclide alteration during biosphere transport	Included	Biosphere	Transport
2.3.13.03.0A	Effects of repository heat on the biosphere	Excluded	Biosphere	Characteristics
2.3.13.04.0A	Radionuclide release outside the reference biosphere	Excluded	Biosphere	Transport
2.4.01.00.0A	Human characteristics (physiology, metabolism)	Included	Biosphere	Characteristics
2.4.04.01.0A	Human lifestyle	Included	Biosphere	Characteristics
2.4.07.00.0A	Dwellings	Included	Biosphere	Characteristics
2.4.08.00.0A	Wild and natural land and water use	Included	Biosphere	Characteristics
2.4.09.01.0A	Implementation of new agricultural practices or land use	Excluded	Biosphere	Characteristics
2.4.09.01.0B	Agricultural land use and irrigation	Included	Biosphere	Characteristics
2.4.09.02.0A	Animal farms and fisheries	Included	Biosphere	Characteristics
2.4.10.00.0A	Urban and industrial land and water use	Included	Biosphere	Characteristics
3.1.01.01.0A	Radioactive decay and ingrowth	Included	Biosphere	Transport
3.1.01.01.0A	Radioactive decay and ingrowth	Included	Invert	Transport
3.1.01.01.0A	Radioactive decay and ingrowth	Included	Saturated Zone	Transport
3.1.01.01.0A	Radioactive decay and ingrowth	Included	Unsaturated Zone Below the Repository	Transport
3.1.01.01.0A	Radioactive decay and ingrowth	Included	Waste Form and Waste Package Internals	Transport

Table 2.2-1. List of Potentially Relevant Features, Events, and Processes (Continued)

FEP Number	FEP Name	Screening Decision	Feature	Process or Event
3.2.07.01.0A	Isotopic dilution	Excluded	Saturated Zone	Transport
3.2.10.00.0A	Atmospheric transport of contaminants	Included	Biosphere	Transport
3.3.01.00.0A	Contaminated drinking water, foodstuffs and drugs	Included	Biosphere	Transport
3.3.02.01.0A	Plant uptake	Included	Biosphere	Transport
3.3.02.02.0A	Animal uptake	Included	Biosphere	Transport
3.3.02.03.0A	Fish uptake	Included	Biosphere	Transport
3.3.03.01.0A	Contaminated nonfood products and exposure	Included	Biosphere	Transport
3.3.04.01.0A	Ingestion	Included	Biosphere	Radiological
3.3.04.02.0A	Inhalation	Included	Biosphere	Radiological
3.3.04.03.0A	External exposure	Included	Biosphere	Radiological
3.3.05.01.0A	Radiation doses	Included	Biosphere	Radiological
3.3.06.00.0A	Radiological toxicity and effects	Excluded	Biosphere	Radiological
3.3.06.01.0A	Repository excavation	Excluded	System	Human Intrusion
3.3.06.02.0A	Sensitization to radiation	Excluded	Biosphere	Radiological
3.3.07.00.0A	Nonradiological toxicity and effects	Excluded	Biosphere	Characteristics
3.3.08.00.0A	Radon and radon decay product exposure	Included	Biosphere	Radiological

NOTE: Repeated FEP numbers indicate that a process applies to multiple features that are included in multiple barriers identified in Section 2.1.1.
CSNF = commercial spent nuclear fuel; DE = disruptive events; DSNF = DOE spent nuclear fuel; MIC = microbially influenced corrosion; SCC = stress corrosion cracking; SZ = saturated zone; UZ = unsaturated zone; WP = waste package.

Source: SNL 2008c; SNL 2008a.

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Topography and Surficial Soils	Characteristics	1.2.02.01.0A	Fractures	Included
Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic	1.2.07.01.0A	Erosion/denudation	Excluded
Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic	1.2.07.02.0A	Deposition	Excluded
Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic	1.3.01.00.0A	Climate change	Included
Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic	1.4.01.01.0A	Climate modification increases recharge	Included
Topography and Surficial Soils	Characteristics	2.2.03.02.0A	Rock properties of host rock and other units	Included
Topography and Surficial Soils	Mechanical and Thermal-Mechanical	2.2.06.04.0A	Effects of subsidence	Excluded
Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic	2.2.07.01.0A	Locally saturated flow at bedrock/alluvium contact	Excluded
Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic	2.2.07.08.0A	Fracture flow in the UZ	Included
Topography and Surficial Soils	Characteristics	2.3.01.00.0A	Topography and morphology	Included
Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic	2.3.11.01.0A	Precipitation	Included
Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic	2.3.11.02.0A	Surface runoff and evapotranspiration	Included
Topography and Surficial Soils	Hydrologic and Thermal-Hydrologic	2.3.11.03.0A	Infiltration and recharge	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	1.1.01.01.0A	Open site investigation boreholes	Excluded
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	1.1.01.01.0B	Influx through holes drilled in drift wall or crown	Excluded
Unsaturated Zone Above the Repository	Characteristics	1.2.02.01.0A	Fractures	Included
Unsaturated Zone Above the Repository	Characteristics	1.2.02.02.0A	Faults	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	1.3.01.00.0A	Climate change	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	1.4.01.01.0A	Climate modification increases recharge	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Unsaturated Zone Above the Repository	Chemical and Thermal-Chemical	1.4.06.01.0A	Altered soil or surface water chemistry	Excluded
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.1.08.01.0A	Water influx at the repository	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.1.08.01.0B	Effects of rapid influx into the repository	Excluded
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.1.08.02.0A	Enhanced influx at the repository	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.1.08.03.0A	Repository dry-out due to waste heat	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.1.08.11.0A	Repository resaturation due to waste cooling	Included
Unsaturated Zone Above the Repository	Chemical and Thermal-Chemical	2.1.09.12.0A	Rind (chemically altered zone) forms in the near-field	Excluded
Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical	2.2.01.01.0A	Mechanical effects of excavation and construction in the near field	Included
Unsaturated Zone Above the Repository	Chemical and Thermal-Chemical	2.2.01.01.0B	Chemical effects of excavation and construction in the near field	Excluded
Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical	2.2.01.02.0A	Thermally-induced stress changes in the near field	Excluded
Unsaturated Zone Above the Repository	Chemical and Thermal-Chemical	2.2.01.02.0B	Chemical changes in the near-field from backfill	Excluded
Unsaturated Zone Above the Repository	Characteristics	2.2.03.01.0A	Stratigraphy	Included
Unsaturated Zone Above the Repository	Characteristics	2.2.03.02.0A	Rock properties of host rock and other units	Included
Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical	2.2.06.04.0A	Effects of subsidence	Excluded
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.01.0A	Locally saturated flow at bedrock/alluvium contact	Excluded
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.02.0A	Unsaturated groundwater flow in the geosphere	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.04.0A	Focusing of unsaturated flow (fingers, weeps)	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.05.0A	Flow in the UZ from episodic infiltration	Excluded
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.07.0A	Perched water develops	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.08.0A	Fracture flow in the UZ	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.09.0A	Matrix imbibition in the UZ	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.10.0A	Condensation zone forms around drifts	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.11.0A	Resaturation of geosphere dry-out zone	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.18.0A	Film flow into the repository	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.19.0A	Lateral flow from Solitario Canyon Fault enters drifts	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.20.0A	Flow diversion around repository drifts	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.10.01.0A	Repository-induced thermal effects on flow in the UZ	Excluded
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.10.03.0B	Natural geothermal effects on flow in the UZ	Included
Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical	2.2.10.04.0A	Thermal-mechanical stresses alter characteristics of fractures near repository	Excluded
Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical	2.2.10.04.0B	Thermal-mechanical stresses alter characteristics of faults near repository	Excluded
Unsaturated Zone Above the Repository	Mechanical and Thermal-Mechanical	2.2.10.05.0A	Thermal-mechanical stresses alter characteristics of rocks above and below the repository	Excluded
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.10.10.0A	Two-phase buoyant flow/heat pipes	Included
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.10.11.0A	Natural air flow in the UZ	Excluded
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.10.12.0A	Geosphere dry-out due to waste heat	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Unsaturated Zone Above the Repository	Hydrologic and Thermal-Hydrologic	2.2.11.02.0A	Gas effects in the UZ	Excluded
Unsaturated Zone Above the Repository	Characteristics	2.2.12.00.0A	Undetected features in the UZ	Excluded
Emplacement Drift	Chemical and Thermal-Chemical	1.1.02.00.0A	Chemical effects of excavation and construction in EBS	Excluded
Emplacement Drift	Mechanical and Thermal-Mechanical	1.1.02.00.0B	Mechanical effects of excavation and construction in EBS	Excluded
Emplacement Drift	Hydrologic and Thermal-Hydrologic	1.1.02.01.0A	Site flooding (during construction and operation)	Excluded
Emplacement Drift	Hydrologic and Thermal-Hydrologic	1.1.02.02.0A	Preclosure ventilation	Included
Emplacement Drift	Characteristics	1.1.02.03.0A	Undesirable materials left	Excluded
Emplacement Drift	Characteristics	1.1.03.01.0A	Error in waste emplacement	Excluded
Emplacement Drift	Characteristics	2.1.01.04.0A	Repository-scale spatial heterogeneity of emplaced waste	Included
Emplacement Drift	Chemical and Thermal-Chemical	2.1.03.09.0A	Copper corrosion in EBS	Excluded
Emplacement Drift	Chemical and Thermal-Chemical	2.1.06.01.0A	Chemical effects of rock reinforcement and cementitious materials in EBS	Excluded
Emplacement Drift	Mechanical and Thermal-Mechanical	2.1.06.02.0A	Mechanical effects of rock reinforcement materials in EBS	Excluded
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.06.04.0A	Flow through rock reinforcement materials in EBS	Excluded
Emplacement Drift	Chemical and Thermal-Chemical	2.1.06.07.0A	Chemical effects at EBS component interfaces	Excluded
Emplacement Drift	Mechanical and Thermal-Mechanical	2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded
Emplacement Drift	Mechanical and Thermal-Mechanical	2.1.07.01.0A	Rockfall	Excluded
Emplacement Drift	Mechanical and Thermal-Mechanical	2.1.07.02.0A	Drift collapse	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Emplacement Drift	Mechanical and Thermal-Mechanical	2.1.07.06.0A	Floor buckling	Excluded
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.08.01.0B	Effects of rapid influx into the repository	Excluded
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.08.03.0A	Repository dry-out due to waste heat	Included
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.08.04.0A	Condensation forms on roofs of drifts (drift-scale cold traps)	Included
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.08.04.0B	Condensation forms at repository edges (repository-scale cold traps)	Included
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.08.06.0A	Capillary effects (wicking) in EBS	Included
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.08.07.0A	Unsaturated flow in the EBS	Included
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.08.09.0A	Saturated flow in the EBS	Excluded
Emplacement Drift	Mechanical and Thermal-Mechanical	2.1.08.15.0A	Consolidation of EBS components	Excluded
Emplacement Drift	Characteristics	2.1.09.01.0A	Chemical characteristics of water in drifts	Included
Emplacement Drift	Chemical and Thermal-Chemical	2.1.09.02.0A	Chemical interaction with corrosion products	Included
Emplacement Drift	Mechanical and Thermal-Mechanical	2.1.09.03.0C	Volume increase of corrosion products impacts other EBS components	Excluded
Emplacement Drift	Chemical and Thermal-Chemical	2.1.09.09.0A	Electrochemical effects in EBS	Excluded
Emplacement Drift	Microbiological	2.1.10.01.0A	Microbial activity in EBS	Excluded
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.11.01.0A	Heat generation in EBS	Included
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.11.02.0A	Nonuniform heat distribution in EBS	Included
Emplacement Drift	Chemical and Thermal-Chemical	2.1.11.03.0A	Exothermic reactions in the EBS	Excluded
Emplacement Drift	Mechanical and Thermal-Mechanical	2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Emplacement Drift	Chemical and Thermal-Chemical	2.1.11.08.0A	Thermal effects on chemistry and microbial activity in the EBS	Included
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.11.09.0A	Thermal effects on flow in the EBS	Included
Emplacement Drift	Hydrologic and Thermal-Hydrologic	2.1.11.09.0C	Thermally driven flow (convection) in drifts	Included
Emplacement Drift	Chemical and Thermal-Chemical	2.1.12.01.0A	Gas generation (repository pressurization)	Excluded
Emplacement Drift	Chemical and Thermal-Chemical	2.1.12.03.0A	Gas generation (H_2) from waste package corrosion	Excluded
Emplacement Drift	Microbiological	2.1.12.04.0A	Gas generation (CO_2, CH_4, H_2S) from microbial degradation	Excluded
Emplacement Drift	Mechanical and Thermal-Mechanical	2.1.12.08.0A	Gas explosions in EBS	Excluded
Emplacement Drift	Radiological	2.1.13.01.0A	Radiolysis	Excluded
Emplacement Drift	Radiological	2.1.13.02.0A	Radiation damage in EBS	Excluded
Emplacement Drift	Radiological	2.1.13.03.0A	Radiological mutation of microbes	Excluded
Emplacement Drift	Chemical and Thermal-Chemical	2.2.01.01.0B	Chemical effects of excavation and construction in the near-field	Excluded
Emplacement Drift	Mechanical and Thermal-Mechanical	2.2.01.02.0A	Thermally induced stress changes in the near-field	Excluded
Emplacement Drift	Transport	2.2.07.06.0B	Long-term release of radionuclides from the repository	Included
Emplacement Drift	Chemical and Thermal-Chemical	2.2.08.03.0B	Geochemical interactions and evolution in the UZ	Excluded
Emplacement Drift	Chemical and Thermal-Chemical	2.2.08.04.0A	Re-dissolution of precipitates directs more corrosive fluids to waste packages	Excluded
Emplacement Drift	Chemical and Thermal-Chemical	2.2.08.12.0A	Chemistry of water flowing into the drift	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Backfill/Seals	Characteristics	1.1.03.01.0B	Error in backfill emplacement	Excluded
Backfill/Seals	Hydrologic and Thermal-Hydrologic	2.1.04.01.0A	Flow in the backfill	Excluded
Backfill/Seals	Chemical and Thermal-Chemical	2.1.04.02.0A	Chemical properties and evolution of backfill	Excluded
Backfill/Seals	Mechanical and Thermal-Mechanical	2.1.04.03.0A	Erosion or dissolution of backfill	Excluded
Backfill/Seals	Mechanical and Thermal-Mechanical	2.1.04.04.0A	Thermal-mechanical effects of backfill	Excluded
Backfill/Seals	Mechanical and Thermal-Mechanical	2.1.04.05.0A	Thermal-mechanical properties and evolution of backfill	Excluded
Backfill/Seals	Transport	2.1.04.09.0A	Radionuclide transport in backfill	Excluded
Backfill/Seals	Hydrologic and Thermal-Hydrologic	2.1.05.01.0A	Flow through seals (access ramps and ventilation shafts)	Excluded
Backfill/Seals	Transport	2.1.05.02.0A	Radionuclide transport through seals	Excluded
Backfill/Seals	Mechanical and Thermal-Mechanical	2.1.05.03.0A	Degradation of seals	Excluded
Backfill/Seals	Chemical and Thermal-Chemical	2.2.01.02.0B	Chemical changes in the near-field from backfill	Excluded
Drip Shield	Chemical and Thermal-Chemical	2.1.03.01.0B	General corrosion of drip shields	Included
Drip Shield	Chemical and Thermal-Chemical	2.1.03.02.0B	Stress corrosion cracking (SCC) of drip shields	Excluded
Drip Shield	Chemical and Thermal-Chemical	2.1.03.03.0B	Localized corrosion of drip shields	Excluded
Drip Shield	Chemical and Thermal-Chemical	2.1.03.04.0B	Hydride cracking of drip shields	Excluded
Drip Shield	Chemical and Thermal-Chemical	2.1.03.05.0B	Microbially influenced corrosion (MIC) of drip shields	Excluded
Drip Shield	Mechanical	2.1.03.07.0B	Mechanical impact on drip shield	Excluded
Drip Shield	Early Failure	2.1.03.08.0B	Early failure of drip shields	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Drip Shield	Hydrologic and Thermal-Hydrologic	2.1.03.10.0B	Advection of liquids and solids through cracks in the drip shield	Excluded
Drip Shield	Characteristics	2.1.03.11.0A	Physical form of waste package and drip shield	Included
Drip Shield	Hydrologic and Thermal-Hydrologic	2.1.06.06.0A	Effects of drip shield on flow	Included
Drip Shield	Chemical and Thermal-Chemical	2.1.06.06.0B	Oxygen embrittlement of drip shields	Excluded
Drip Shield	Chemical and Thermal-Chemical	2.1.06.07.0A	Chemical effects at EBS component interfaces	Excluded
Drip Shield	Mechanical and Thermal-Mechanical	2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded
Drip Shield	Mechanical and Thermal-Mechanical	2.1.07.01.0A	Rockfall	Excluded
Drip Shield	Mechanical and Thermal-Mechanical	2.1.07.04.0B	Hydrostatic pressure on drip shield	Excluded
Drip Shield	Mechanical and Thermal-Mechanical	2.1.07.05.0B	Creep of metallic materials in the drip shield	Excluded
Drip Shield	Hydrologic and Thermal-Hydrologic	2.1.08.14.0A	Condensation on underside of drip shield	Excluded
Drip Shield	Mechanical and Thermal-Chemical	2.1.08.15.0A	Consolidation of EBS components	Excluded
Drip Shield	Chemical and Thermal-Chemical	2.1.09.28.0B	Localized corrosion on drip shield surface due to deliquescence	Excluded
Drip Shield	Chemical and Thermal-Chemical	2.1.11.06.0B	Thermal sensitization of drip shields	Excluded
Drip Shield	Mechanical and Thermal-Mechanical	2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded
Drip Shield	Radiological	2.1.13.02.0A	Radiation damage in EBS screening decision	Excluded
Waste Package	Chemical and Thermal-Chemical	2.1.03.01.0A	General corrosion of waste packages	Included
Waste Package	Chemical and Thermal-Chemical	2.1.03.02.0A	Stress corrosion cracking (SCC) of waste packages	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Waste Package	Chemical and Thermal-Chemical	2.1.03.03.0A	Localized corrosion of waste packages	Included
Waste Package	Chemical and Thermal-Chemical	2.1.03.04.0A	Hydride cracking of waste packages	Excluded
Waste Package	Chemical and Thermal-Chemical	2.1.03.05.0A	Microbially influenced corrosion (MIC) of waste packages	Included
Waste Package	Chemical and Thermal-Chemical	2.1.03.06.0A	Internal corrosion of waste packages prior to breach	Excluded
Waste Package	Chemical and Thermal-Chemical	2.1.09.28.0A	Localized corrosion on waste package outer surface due to deliquescence	Excluded
Waste Package	Mechanical	2.1.03.07.0A	Mechanical impact on waste package	Excluded
Waste Package	Early Failure	2.1.03.08.0A	Early failure of waste packages	Included
Waste Package	Hydrologic and Thermal-Hydrologic	2.1.03.10.0A	Advection of liquids and solids through cracks in the waste package	Excluded
Waste Package	Characteristics	2.1.03.11.0A	Physical form of waste package and drip shield	Included
Waste Package	Mechanical and Thermal-Mechanical	2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded
Waste Package	Mechanical and Thermal-Mechanical	2.1.07.01.0A	Rockfall	Excluded
Waste Package	Mechanical and Thermal-Mechanical	2.1.07.04.0A	Hydrostatic pressure on waste package	Excluded
Waste Package	Mechanical and Thermal-Mechanical	2.1.07.05.0A	Creep of metallic materials in the waste package	Excluded
Waste Package	Mechanical and Thermal-Mechanical	2.1.08.15.0A	Consolidation of EBS components	Excluded
Waste Package	Mechanical and Thermal-Mechanical	2.1.09.03.0B	Volume increase of corrosion products impacts waste package	Excluded
Waste Package	Chemical and Thermal-Chemical	2.1.11.03.0A	Exothermic reactions in the EBS	Excluded
Waste Package	Chemical and Thermal-Chemical	2.1.11.06.0A	Thermal sensitization of waste packages	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Waste Package	Mechanical and Thermal-Mechanical	2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded
Waste Package	Chemical and Thermal-Chemical	2.1.12.03.0A	Gas generation (H_2) from waste package corrosion	Excluded
Waste Package	Radiological	2.1.13.01.0A	Radiolysis	Excluded
Waste Package	Radiological	2.1.13.02.0A	Radiation damage in EBS screening decision	Excluded
Cladding	Mechanical and Thermal-Mechanical	2.1.02.11.0A	Degradation of cladding from waterlogged rods	Excluded
Cladding	Mechanical and Thermal-Mechanical	2.1.02.12.0A	Degradation of cladding prior to disposal	Included
Cladding	Chemical and Thermal-Chemical	2.1.02.13.0A	General corrosion of cladding	Excluded
Cladding	Chemical and Thermal-Chemical	2.1.02.14.0A	Microbially influenced corrosion (MIC) of cladding	Excluded
Cladding	Chemical and Thermal-Chemical	2.1.02.15.0A	Localized (radiolysis enhanced) corrosion of cladding	Excluded
Cladding	Chemical and Thermal-Chemical	2.1.02.16.0A	Localized (pitting) corrosion of cladding	Excluded
Cladding	Chemical and Thermal-Chemical	2.1.02.17.0A	Localized (crevice) corrosion of cladding	Excluded
Cladding	Chemical and Thermal-Chemical	2.1.02.18.0A	Enhanced corrosion of cladding from dissolved silica	Excluded
Cladding	Mechanical and Thermal-Mechanical	2.1.02.19.0A	Creep rupture of cladding	Excluded
Cladding	Mechanical and Thermal-Mechanical	2.1.02.20.0A	Internal pressurization of cladding	Excluded
Cladding	Chemical and Thermal-Chemical	2.1.02.21.0A	Stress corrosion cracking (SCC) of cladding	Excluded
Cladding	Chemical and Thermal-Chemical	2.1.02.22.0A	Hydride cracking of cladding	Excluded
Cladding	Mechanical and Thermal-Mechanical	2.1.02.23.0A	Cladding unzipping	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Cladding	Mechanical and Thermal-Mechanical	2.1.02.24.0A	Mechanical impact on cladding	Excluded
Cladding	Mechanical and Thermal-Mechanical	2.1.02.25.0A	DSNF cladding	Excluded
Cladding	Mechanical and Thermal-Mechanical	2.1.02.25.0B	Naval SNF Cladding	Included
Cladding	Mechanical and Thermal-Mechanical	2.1.02.26.0A	Diffusion-controlled cavity growth in cladding	Excluded
Cladding	Chemical and Thermal-Chemical	2.1.02.27.0A	Localized (fluoride enhanced) corrosion of cladding	Excluded
Cladding	Mechanical and Thermal-Mechanical	2.1.08.15.0A	Consolidation of EBS Components	Excluded
Cladding	Mechanical and Thermal-Mechanical	2.1.09.03.0A	Volume increase of corrosion products impacts cladding	Excluded
Waste Form and Waste Package Internals	Characteristics	2.1.01.01.0A	Waste inventory	Included
Waste Form and Waste Package Internals	Characteristics	2.1.01.02.0A	Interactions between co-located waste	Excluded
Waste Form and Waste Package Internals	Characteristics	2.1.01.02.0B	Interactions between co-disposed waste	Included
Waste Form and Waste Package Internals	Characteristics	2.1.01.03.0A	Heterogeneity of waste inventory	Included
Waste Form and Waste Package Internals	Characteristics	2.1.01.04.0A	Repository-scale spatial heterogeneity of emplaced waste	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.02.01.0A	DSNF degradation (alteration, dissolution, and radionuclide release)	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.02.02.0A	CSNF degradation (alteration, dissolution, and radionuclide release)	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.02.03.0A	HLW glass degradation (alteration, dissolution, and radionuclide release)	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.02.04.0A	Alpha recoil enhances dissolution	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Waste Form and Waste Package Internals	Mechanical and Thermal-Mechanical	2.1.02.05.0A	HLW glass cracking	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.02.06.0A	HLW glass recrystallization	Excluded
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.02.07.0A	Radionuclide release from gap and grain boundaries	Included
Waste Form and Waste Package Internals	Characteristics	2.1.02.08.0A	Pyrophoricity from DSNF	Excluded
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.02.09.0A	Chemical effects of void space in waste package	Included
Waste Form and Waste Package Internals	Characteristics	2.1.02.10.0A	Organic/cellulosic materials in waste	Excluded
Waste Form and Waste Package Internals	Characteristics	2.1.02.28.0A	Grouping of DSNF waste types into categories	Included
Waste Form and Waste Package Internals	Characteristics	2.1.02.29.0A	Flammable gas generation from DSNF	Excluded
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.03.06.0A	Internal corrosion of waste packages prior to breach	Excluded
Waste Form and Waste Package Internals	Mechanical and Thermal-Mechanical	2.1.08.15.0A	Consolidation of EBS Components	Excluded
Waste Form and Waste Package Internals	Characteristics	2.1.09.01.0B	Chemical characteristics of water in waste package	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.09.02.0A	Chemical interaction with corrosion products	Included
Waste Form and Waste Package Internals	Transport	2.1.09.04.0A	Radionuclide solubility, solubility limits, and speciation in the waste form and EBS	Included
Waste Form and Waste Package Internals	Transport	2.1.09.05.0A	Sorption of dissolved radionuclides in EBS	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.09.06.0A	Reduction-oxidation potential in waste package	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.09.07.0A	Reaction kinetics in waste package	Included
Waste Form and Waste Package Internals	Transport	2.1.09.08.0A	Diffusion of dissolved radionuclides in EBS	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Waste Form and Waste Package Internals	Transport	2.1.09.08.0B	Advection of dissolved radionuclides in EBS	Included
Waste Form and Waste Package Internals	Transport	2.1.09.10.0A	Secondary phase effects on dissolved radionuclide concentrations	Excluded
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.09.11.0A	Chemical effects of waste–rock contact	Excluded
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.09.15.0A	Formation of true (intrinsic) colloids in EBS	Excluded
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.09.16.0A	Formation of pseudo-colloids (natural) in EBS	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.09.17.0A	Formation of pseudo-colloids (corrosion product) in EBS	Included
Waste Form and Waste Package Internals	Microbiological	2.1.09.18.0A	Formation of microbial colloids in EBS	Excluded
Waste Form and Waste Package Internals	Transport	2.1.09.19.0A	Sorption of colloids in EBS	Excluded
Waste Form and Waste Package Internals	Transport	2.1.09.19.0B	Advection of colloids in EBS	Included
Waste Form and Waste Package Internals	Transport	2.1.09.20.0A	Filtration of colloids in EBS	Excluded
Waste Form and Waste Package Internals	Transport	2.1.09.23.0A	Stability of colloids in EBS	Included
Waste Form and Waste Package Internals	Transport	2.1.09.24.0A	Diffusion of colloids in EBS	Included
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.09.25.0A	Formation of colloids (waste form) by co-precipitation in EBS	Included
Waste Form and Waste Package Internals	Mechanical and Thermal-Mechanical	2.1.11.05.0A	Thermal expansion/stress of in-package EBS components	Excluded
Waste Form and Waste Package Internals	Hydrologic and Thermal-Hydrologic	2.1.11.09.0B	Thermally driven flow (convection) in waste packages	Excluded
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.1.12.02.0A	Gas generation (He) from waste form decay	Excluded
Waste Form and Waste Package Internals	Chemical and Thermal-Chemical	2.2.08.12.0B	Chemistry of water flowing into the waste package	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Waste Form and Waste Package Internals	Transport	3.1.01.01.0A	Radioactive decay and ingrowth	Included
Waste Package Pallet	Mechanical and Thermal-Mechanical	2.1.06.05.0A	Mechanical degradation of emplacement pallet	Excluded
Waste Package Pallet	Chemical and Thermal-Chemical	2.1.06.05.0C	Chemical degradation of emplacement pallet	Included
Waste Package Pallet	Chemical and Thermal-Chemical	2.1.06.07.0A	Chemical effects at EBS component interfaces	Excluded
Waste Package Pallet	Mechanical and Thermal Mechanical	2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded
Waste Package Pallet	Mechanical and Thermal Mechanical	2.1.08.15.0A	Consolidation of EBS Components	Excluded
Waste Package Pallet	Mechanical and Thermal-Mechanical	2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded
Invert	Mechanical and Thermal-Mechanical	2.1.06.05.0B	Mechanical degradation of invert	Excluded
Invert	Chemical and Thermal-Chemical	2.1.06.05.0D	Chemical degradation of invert	Excluded
Invert	Mechanical and Thermal-Mechanical	2.1.06.07.0B	Mechanical effects at EBS component interfaces	Excluded
Invert	Hydrologic and Thermal-Hydrologic	2.1.08.05.0A	Flow through invert	Included
Invert	Hydrologic and Thermal-Hydrologic	2.1.08.06.0A	Capillary effects (wicking) in EBS	Included
Invert	Hydrologic and Thermal-Hydrologic	2.1.08.07.0A	Unsaturated Flow in the EBS	Included
Invert	Hydrologic and Thermal-Hydrologic	2.1.08.12.0A	Induced hydrologic changes in invert	Excluded
Invert	Mechanical and Thermal Mechanical	2.1.08.15.0A	Consolidation of EBS Components	Excluded
Invert	Characteristics	2.1.09.01.0A	Chemical characteristics of water in drifts	Included
Invert	Transport	2.1.09.04.0A	Radionuclide solubility, solubility limits, and speciation in the waste form and EBS	Included
Invert	Transport	2.1.09.05.0A	Sorption of dissolved radionuclides in EBS	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Invert	Chemical and Thermal-Chemical	2.1.09.06.0B	Reduction-oxidation potential in drifts	Included
Invert	Chemical and Thermal-Chemical	2.1.09.07.0B	Reaction kinetics in drifts	Included
Invert	Transport	2.1.09.08.0A	Diffusion of dissolved radionuclides in EBS	Included
Invert	Transport	2.1.09.08.0B	Advection of dissolved radionuclides in EBS	Included
Invert	Microbiological	2.1.09.13.0A	Complexation in EBS	Excluded
Invert	Transport	2.1.09.19.0A	Sorption of colloids in EBS	Excluded
Invert	Transport	2.1.09.19.0B	Advection of colloids in EBS	Included
Invert	Transport	2.1.09.20.0A	Filtration of colloids in EBS	Excluded
Invert	Transport	2.1.09.21.0A	Transport of particles larger than colloids in EBS	Excluded
Invert	Transport	2.1.09.22.0A	Sorption of colloids at air–water interface	Excluded
Invert	Transport	2.1.09.23.0A	Stability of colloids in EBS	Included
Invert	Transport	2.1.09.24.0A	Diffusion of colloids in EBS	Included
Invert	Transport	2.1.09.26.0A	Gravitational settling of colloids in EBS	Excluded
Invert	Transport	2.1.09.27.0A	Coupled effects on radionuclide transport in EBS	Excluded
Invert	Mechanical and Thermal-Mechanical	2.1.11.07.0A	Thermal expansion/stress of in-drift EBS components	Excluded
Invert	Transport	2.1.11.10.0A	Thermal effects on transport in EBS	Excluded
Invert	Transport	2.1.12.06.0A	Gas transport in EBS	Excluded
Invert	Transport	2.1.12.07.0A	Effects of radioactive gases in EBS	Excluded
Invert	Transport	2.2.07.06.0A	Episodic or pulse release from repository	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Invert	Transport	2.2.07.06.0B	Long-term release of radionuclides from the repository	Included
Invert	Transport	3.1.01.01.0A	Radioactive decay and ingrowth	Included
Unsaturated Zone Below the Repository	Characteristics	1.2.02.01.0A	Fractures	Included
Unsaturated Zone Below the Repository	Characteristics	1.2.02.02.0A	Faults	Included
Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic	1.3.01.00.0A	Climate change	Included
Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic	1.3.07.02.0B	Water table rise affects UZ	Included
Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic	1.4.01.01.0A	Climate modification increases recharge	Included
Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical	2.1.09.12.0A	Rind (chemically altered zone) forms in the near-field	Excluded
Unsaturated Zone Below the Repository	Transport	2.1.09.21.0C	Transport of particles larger than colloids in the UZ	Excluded
Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical	2.2.01.02.0B	Chemical changes in the near-field from backfill	Excluded
Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic	2.2.01.03.0A	Changes in fluid saturations in the excavation disturbed zone	Excluded
Unsaturated Zone Below the Repository	Transport	2.2.01.04.0A	Radionuclide solubility in the excavation disturbed zone	Excluded
Unsaturated Zone Below the Repository	Transport	2.2.01.05.0A	Radionuclide transport in the excavation disturbed zone	Excluded
Unsaturated Zone Below the Repository	Characteristics	2.2.03.01.0A	Stratigraphy	Included
Unsaturated Zone Below the Repository	Characteristics	2.2.03.02.0A	Rock properties of host rock and other units	Included
Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.02.0A	Unsaturated groundwater flow in the geosphere	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.03.0A	Capillary rise in the UZ	Included
Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.07.0A	Perched water develops	Included
Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.08.0A	Fracture flow in the UZ	Included
Unsaturated Zone Below the Repository	Hydrologic and Thermal-Hydrologic	2.2.07.09.0A	Matrix imbibition in the UZ	Included
Unsaturated Zone Below the Repository	Transport	2.2.07.15.0B	Advection and dispersion in the UZ	Included
Unsaturated Zone Below the Repository	Transport	2.2.07.21.0A	Drift shadow forms below repository	Excluded
Unsaturated Zone Below the Repository	Characteristics	2.2.08.01.0B	Chemical characteristics of groundwater in the UZ	Included
Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical	2.2.08.03.0B	Geochemical interactions and evolution in the UZ	Excluded
Unsaturated Zone Below the Repository	Transport	2.2.08.05.0A	Diffusion in the UZ	Excluded
Unsaturated Zone Below the Repository	Microbiological	2.2.08.06.0B	Complexation in the UZ	Included
Unsaturated Zone Below the Repository	Transport	2.2.08.07.0B	Radionuclide solubility limits in the UZ	Excluded
Unsaturated Zone Below the Repository	Transport	2.2.08.08.0B	Matrix diffusion in the UZ	Included
Unsaturated Zone Below the Repository	Transport	2.2.08.09.0B	Sorption in the UZ	Included
Unsaturated Zone Below the Repository	Transport	2.2.08.10.0B	Colloidal transport in the UZ	Included
Unsaturated Zone Below the Repository	Microbiological	2.2.09.01.0B	Microbial activity in the UZ	Excluded
Unsaturated Zone Below the Repository	Mechanical and Thermal-Mechanical	2.2.10.04.0A	Thermal-mechanical stresses alter characteristics of fractures near repository	Excluded
Unsaturated Zone Below the Repository	Mechanical and Thermal-Mechanical	2.2.10.04.0B	Thermal-mechanical stresses alter characteristics of faults near repository	Excluded
Unsaturated Zone Below the Repository	Mechanical and Thermal-Mechanical	2.2.10.05.0A	Thermal-mechanical stresses alter characteristics of rocks above and below the repository	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical	2.2.10.06.0A	Thermal-chemical alteration in the UZ (solubility, speciation, phase changes, precipitation/dissolution)	Excluded
Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical	2.2.10.07.0A	Thermal-chemical alteration of the Calico Hills unit	Excluded
Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical	2.2.10.09.0A	Thermal-chemical alteration of the Topopah Spring basal vitrophyre	Excluded
Unsaturated Zone Below the Repository	Chemical and Thermal-Chemical	2.2.10.14.0A	Mineralogic dehydration reactions	Excluded
Unsaturated Zone Below the Repository	Transport	2.2.11.03.0A	Gas transport in geosphere	Excluded
Unsaturated Zone Below the Repository	Characteristics	2.2.12.00.0A	Undetected features in the UZ	Excluded
Unsaturated Zone Below the Repository	Transport	3.1.01.01.0A	Radioactive decay and ingrowth	Included
Saturated Zone	Characteristics	1.2.02.01.0A	Fractures	Included
Saturated Zone	Characteristics	1.2.02.02.0A	Faults	Included
Saturated Zone	Chemical and Thermal-Chemical	1.2.09.02.0A	Large-scale dissolution	Excluded
Saturated Zone	Hydrologic and Thermal-Hydrologic	1.3.01.00.0A	Climate change	Included
Saturated Zone	Hydrologic and Thermal-Hydrologic	1.3.07.01.0A	Water table decline	Excluded
Saturated Zone	Hydrologic and Thermal-Hydrologic	1.3.07.02.0A	Water table rise affects SZ	Included
Saturated Zone	Hydrologic and Thermal-Hydrologic	1.4.01.01.0A	Climate modification increases recharge	Included
Saturated Zone	Transport	1.4.07.02.0A	Wells	Included
Saturated Zone	Transport	2.1.09.21.0B	Transport of particles larger than colloids in the SZ	Excluded
Saturated Zone	Characteristics	2.2.03.01.0A	Stratigraphy	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Saturated Zone	Characteristics	2.2.03.02.0A	Rock properties of host rock and other units	Included
Saturated Zone	Hydrologic and Thermal-Hydrologic	2.2.07.12.0A	Saturated groundwater flow in the geosphere	Included
Saturated Zone	Characteristics	2.2.07.13.0A	Water-conducting features in the SZ	Included
Saturated Zone	Characteristics	2.2.07.14.0A	Chemically induced density effects on groundwater flow	Excluded
Saturated Zone	Transport	2.2.07.15.0A	Advection and dispersion in the SZ	Included
Saturated Zone	Transport	2.2.07.16.0A	Dilution of radionuclides in groundwater	Included
Saturated Zone	Transport	2.2.07.17.0A	Diffusion in the SZ	Included
Saturated Zone	Characteristics	2.2.08.01.0A	Chemical characteristics of groundwater in the SZ	Included
Saturated Zone	Chemical and Thermal-Chemical	2.2.08.03.0A	Geochemical interactions and evolution in the SZ	Excluded
Saturated Zone	Microbiological	2.2.08.06.0A	Complexation in the SZ	Included
Saturated Zone	Transport	2.2.08.07.0A	Radionuclide solubility limits in the SZ	Excluded
Saturated Zone	Transport	2.2.08.08.0A	Matrix diffusion in the SZ	Included
Saturated Zone	Transport	2.2.08.09.0A	Sorption in the SZ	Included
Saturated Zone	Transport	2.2.08.10.0A	Colloidal transport in the SZ	Included
Saturated Zone	Microbiological	2.2.09.01.0A	Microbial activity in the SZ	Excluded
Saturated Zone	Hydrologic and Thermal-Hydrologic	2.2.10.02.0A	Thermal convection cell develops in SZ	Excluded
Saturated Zone	Hydrologic and Thermal-Hydrologic	2.2.10.03.0A	Natural geothermal effects on flow in the SZ	Included
Saturated Zone	Chemical and Thermal-Chemical	2.2.10.08.0A	Thermal-chemical alteration in the SZ (solubility, speciation, phase changes, precipitation/dissolution)	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Saturated Zone	Hydrologic and Thermal-Hydrologic	2.2.10.13.0A	Repository-induced thermal effects on flow in the SZ	Excluded
Saturated Zone	Hydrologic and Thermal-Hydrologic	2.2.11.01.0A	Gas effects in the SZ	Excluded
Saturated Zone	Characteristics	2.2.12.00.0B	Undetected features in the SZ	Included
Saturated Zone	Transport	3.1.01.01.0A	Radioactive decay and ingrowth	Included
Saturated Zone	Transport	3.2.07.01.0A	Isotopic dilution	Excluded
Biosphere	Characteristics	1.4.01.00.0A	Human influences on climate	Excluded
Biosphere	Characteristics	1.4.01.02.0A	Greenhouse gas effects	Excluded
Biosphere	Characteristics	1.4.01.03.0A	Acid rain	Excluded
Biosphere	Characteristics	1.4.01.04.0A	Ozone layer failure	Excluded
Biosphere	Characteristics	1.4.07.01.0A	Water management activities	Included
Biosphere	Transport	1.4.07.03.0A	Recycling of accumulated radionuclides from soils to groundwater	Excluded
Biosphere	Characteristics	1.4.08.00.0A	Social and institutional developments	Excluded
Biosphere	Characteristics	1.4.09.00.0A	Technological developments	Excluded
Biosphere	Characteristics	1.5.02.00.0A	Species evolution	Excluded
Biosphere	Transport	2.2.08.07.0C	Radionuclide solubility limits in the biosphere	Excluded
Biosphere	Transport	2.2.08.11.0A	Groundwater discharge to surface within the reference biosphere	Excluded
Biosphere	Characteristics	2.3.02.01.0A	Soil type	Included
Biosphere	Transport	2.3.02.02.0A	Radionuclide accumulation in soils	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Biosphere	Transport	2.3.02.03.0A	Soil and sediment transport in the biosphere	Included
Biosphere	Transport	2.3.04.01.0A	Surface water transport and mixing	Included
Biosphere	Transport	2.3.09.01.0A	Animal burrowing/intrusion	Excluded
Biosphere	Hydrologic and Thermal-Hydrologic	2.3.11.01.0A	Precipitation	Included
Biosphere	Transport	2.3.11.04.0A	Groundwater discharge to surface outside the reference biosphere	Excluded
Biosphere	Characteristics	2.3.13.01.0A	Biosphere characteristics	Included
Biosphere	Transport	2.3.13.02.0A	Radionuclide alteration during biosphere transport	Included
Biosphere	Characteristics	2.3.13.03.0A	Effects of repository heat on the biosphere	Excluded
Biosphere	Transport	2.3.13.04.0A	Radionuclide release outside the reference biosphere	Excluded
Biosphere	Characteristics	2.4.01.00.0A	Human characteristics (physiology, metabolism)	Included
Biosphere	Characteristics	2.4.04.01.0A	Human lifestyle	Included
Biosphere	Characteristics	2.4.07.00.0A	Dwellings	Included
Biosphere	Characteristics	2.4.08.00.0A	Wild and natural land and water use	Included
Biosphere	Characteristics	2.4.09.01.0A	Implementation of new agricultural practices or land use	Excluded
Biosphere	Characteristics	2.4.09.01.0B	Agricultural land use and irrigation	Included
Biosphere	Characteristics	2.4.09.02.0A	Animal farms and fisheries	Included
Biosphere	Characteristics	2.4.10.00.0A	Urban and industrial land and water use	Included
Biosphere	Transport	3.1.01.01.0A	Radioactive decay and ingrowth	Included

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Biosphere	Transport	3.2.10.00.0A	Atmospheric transport of contaminants	Included
Biosphere	Transport	3.3.01.00.0A	Contaminated drinking water, foodstuffs and drugs	Included
Biosphere	Transport	3.3.02.01.0A	Plant uptake	Included
Biosphere	Transport	3.3.02.02.0A	Animal uptake	Included
Biosphere	Transport	3.3.02.03.0A	Fish uptake	Included
Biosphere	Transport	3.3.03.01.0A	Contaminated nonfood products and exposure	Included
Biosphere	Radiological	3.3.04.01.0A	Ingestion	Included
Biosphere	Radiological	3.3.04.02.0A	Inhalation	Included
Biosphere	Radiological	3.3.04.03.0A	External exposure	Included
Biosphere	Radiological	3.3.05.01.0A	Radiation doses	Included
Biosphere	Radiological	3.3.06.00.0A	Radiological toxicity and effects	Excluded
Biosphere	Radiological	3.3.06.02.0A	Sensitization to radiation	Excluded
Biosphere	Characteristics	3.3.07.00.0A	Nonradiological toxicity and effects	Excluded
Biosphere	Radiological	3.3.08.00.0A	Radon and radon decay product exposure	Included
System	Characteristics	0.1.02.00.0A	Timescales of concern	Included
System	Characteristics	0.1.03.00.0A	Spatial domain of concern	Included
System	Characteristics	0.1.09.00.0A	Regulatory requirements and exclusions	Included
System	Characteristics	0.1.10.00.0A	Model and data issues	Included
System	Characteristics	1.1.04.01.0A	Incomplete closure	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
System	Characteristics	1.1.07.00.0A	Repository design	Included
System	Characteristics	1.1.08.00.0A	Inadequate quality control and deviations from design	Excluded
System	Characteristics	1.1.09.00.0A	Schedule and planning	Included
System	Characteristics	1.1.11.00.0A	Monitoring of the repository	Excluded
System	Characteristics	1.1.12.01.0A	Accidents and unplanned events during construction and operation	Excluded
System	Characteristics	1.1.13.00.0A	Retrievability	Included
System	Characteristics	1.2.01.01.0A	Tectonic activity —large scale	Excluded
System	Characteristics	1.2.05.00.0A	Metamorphism	Excluded
System	Characteristics	1.2.08.00.0A	Diagenesis	Excluded
System	Characteristics	1.2.09.00.0A	Salt diapirism and dissolution	Excluded
System	Characteristics	1.2.09.01.0A	Diapirism	Excluded
System	Characteristics	1.3.04.00.0A	Periglacial effects	Excluded
System	Characteristics	1.3.05.00.0A	Glacial and ice sheet effect	Excluded
System	Characteristics	1.5.01.01.0A	Meteorite impact	Excluded
System	Characteristics	1.5.01.02.0A	Extraterrestrial events	Excluded
System	Characteristics	1.5.03.01.0A	Changes in the earth's magnetic field	Excluded
System	Characteristics	1.5.03.02.0A	Earth tides	Excluded
System	Characteristics	2.2.06.05.0A	Salt creep	Excluded
System	Characteristics	2.3.06.00.0A	Marine features	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Emplacement Drift, Drip Shield, Waste Package, Cladding, Waste Form and Waste Package Internals, Waste Package Pallet, Invert	Seismic	1.2.02.03.0A	Fault displacement damages EBS components	Included
Emplacement Drift, Drip Shield, Waste Package, Cladding, Waste Form and Waste Package Internals, Waste Package Pallet, Invert	Seismic	1.2.03.02.0A	Seismic ground motion damages EBS components	Included
Emplacement Drift, Drip Shield, Waste Package, Cladding, Waste Form and Waste Package Internals, Waste Package Pallet, Invert	Seismic	1.2.03.02.0B	Seismic-induced rockfall damages EBS components	Excluded
Emplacement Drift, Drip Shield, Waste Package, Cladding, Waste Form and Waste Package Internals, Waste Package Pallet, Invert	Seismic	1.2.03.02.0C	Seismic-induced drift collapse damages EBS components	Included
Emplacement Drift	Seismic	1.2.03.02.0D	Seismic-induced drift collapse alters in-drift thermal-hydrology	Included
Emplacement Drift	Seismic	1.2.03.02.0E	Seismic-induced drift collapse alters in-drift chemistry	Excluded
Emplacement Drift	Seismic	1.2.03.03.0A	Seismicity associated with igneous activity	Included
Unsaturated Zone Above Repository, Unsaturated Zone Below Repository, Saturated Zone	Seismic	1.2.10.01.0A	Hydrologic response to seismic activity	Excluded
Unsaturated Zone Above Repository, Unsaturated Zone Below Repository, Saturated Zone	Seismic	2.2.06.01.0A	Seismic activity changes porosity and permeability of rock	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Unsaturated Zone Above Repository, Unsaturated Zone Below Repository, Saturated Zone	Seismic	2.2.06.02.0A	Seismic activity changes porosity and permeability of faults	Excluded
Unsaturated Zone Above Repository, Unsaturated Zone Below Repository, Saturated Zone	Seismic	2.2.06.02.0B	Seismic activity changes porosity and permeability of fractures	Excluded
Unsaturated Zone Above Repository, Unsaturated Zone Below Repository,	Seismic	2.2.06.03.0A	Seismic activity alters perched water zones	Excluded
Biosphere	Igneous	1.2.04.07.0A	Ashfall	Included
Biosphere	Igneous	1.2.04.07.0C	Ash redistribution via soil and sediment transport	Included
Emplacement Drift	Igneous	1.2.03.03.0A	Seismicity associated with igneous activity	Included
Emplacement Drift	Igneous	1.2.04.03.0A	Igneous intrusion into repository	Included
Emplacement Drift, Drip Shield, Waste Package, Cladding, Waste Form and Waste Package Internals, Waste Package Pallet, Invert	Igneous	1.2.04.04.0A	Igneous intrusion interacts with EBS components	Included
Emplacement Drift	Igneous	1.2.04.04.0B	Chemical effects of magma and magmatic volatiles	Included
Emplacement Drift	Igneous	1.2.04.05.0A	Magma or pyroclastic base surge transports waste	Excluded
Emplacement Drift	Igneous	1.2.04.06.0A	Eruptive conduit to surface intersects repository	Included
Saturated Zone	Igneous	1.2.04.07.0B	Ash redistribution in groundwater	Excluded
Unsaturated Zone Above the Repository Unsaturated Zone Below the Repository Saturated Zone	Igneous	1.2.04.02.0A	Igneous activity changes rock properties	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Unsaturated Zone Above the Repository Unsaturated Zone Below the Repository Saturated Zone	Igneous	1.2.10.02.0A	Hydrologic response to igneous activity	Excluded
Unsaturated Zone Above the Repository Unsaturated Zone Below the Repository Saturated Zone	Igneous	1.2.06.00.0A	Hydrothermal activity	Excluded
Invert	Criticality	2.1.14.17.0A	Near-field criticality	Excluded
Invert	Criticality	2.1.14.20.0A	Near-field criticality resulting from a seismic event	Excluded
Invert	Criticality	2.1.14.23.0A	Near-field criticality resulting from rockfall	Excluded
Invert	Criticality	2.1.14.26.0A	Near-field criticality resulting from an igneous event	Excluded
Unsaturated Zone Below the Repository	Criticality	2.2.14.09.0A	Far-field criticality	Excluded
Unsaturated Zone Below the Repository	Criticality	2.2.14.10.0A	Far-field criticality resulting from a seismic event	Excluded
Unsaturated Zone Below the Repository	Criticality	2.2.14.11.0A	Far-field criticality resulting from rockfall	Excluded
Unsaturated Zone Below the Repository	Criticality	2.2.14.12.0A	Far-field criticality resulting from an igneous event	Excluded
Waste Package	Criticality	2.1.14.15.0A	In-package criticality (intact configuration)	Excluded
Waste Package	Criticality	2.1.14.16.0A	In-package criticality (degraded configurations)	Excluded
Waste Package	Criticality	2.1.14.18.0A	In-package criticality resulting from a seismic event (intact configuration)	Excluded
Waste Package	Criticality	2.1.14.19.0A	In-package criticality resulting from a seismic event (degraded configurations)	Excluded
Waste Package	Criticality	2.1.14.21.0A	In-package criticality resulting from rockfall (intact configuration)	Excluded

Table 2.2-2. Mapping of Potentially Relevant Features, Events, and Processes Categorized by Feature and Event (Continued)

Feature	Process or Event	FEP Number	FEP Name	Screening Decision
Waste Package	Criticality	2.1.14.22.0A	In-package criticality resulting from rockfall (degraded configurations)	Excluded
Waste Package	Criticality	2.1.14.24.0A	In-package criticality resulting from an igneous event (intact configuration)	Excluded
Waste Package	Criticality	2.1.14.25.0A	In-package criticality resulting from an igneous event (degraded configurations)	Excluded
System	Human Intrusion	1.4.02.01.0A	Deliberate human intrusion	Excluded
System	Human Intrusion	1.4.02.02.0A	Inadvertent human intrusion	Included
System	Human Intrusion	1.4.03.00.0A	Unintrusive site investigation	Excluded
System	Human Intrusion	1.4.04.00.0A	Drilling activities (human intrusion)	Included
System	Human Intrusion	1.4.04.01.0A	Effects of drilling intrusion	Included
System	Human Intrusion	1.4.05.00.0A	Mining and other underground activities (human intrusion)	Excluded
System	Human Intrusion	1.4.11.00.0A	Explosions and crashes (human activities)	Excluded
System	Human Intrusion	3.3.06.01.0A	Repository excavation	Excluded
System	Human Intrusion	1.1.05.00.0A	Records and markers for the repository	Excluded
System	Human Intrusion	1.1.10.00.0A	Administrative control of the repository site	Excluded
System	Human Intrusion	1.4.02.03.0A	Igneous event precedes human intrusion	Excluded
System	Human Intrusion	1.4.02.04.0A	Seismic event precedes human intrusion	Excluded

NOTE: CSNF = commercial spent nuclear fuel; DSNF = DOE spent nuclear fuel; MIC = microbially influenced corrosion; SCC = stress corrosion cracking; SZ = saturated zone; UZ = unsaturated zone.

Source: SNL 2008c; SNL 2008a.

Table 2.2-3. Repository Design Use in Performance Assessment

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
01-01 Repository Geographic and Geologic Location	FEP 0.1.03.00.0A – Spatial domain of concern FEP 1.1.01.01.0A – Open site investigation boreholes (Excluded) FEP 1.1.07.00.0A – Repository Design FEP 2.1.06.01.0A – Chemical effects of rock reinforcement and cementitious materials in EBS (Excluded) FEP 2.1.07.04.0A – Hydrostatic pressure on waste package (Excluded) FEP 2.1.07.04.0B – Hydrostatic pressure on drip shield (Excluded) FEP 2.1.08.09.0A – Saturated flow in the EBS (Excluded) FEP 2.2.08.03.0B – Geochemical interactions and evolution in the UZ (Excluded) FEP 2.2.08.12.0A – Chemistry of water flowing into the drift	Supports spatial domain of concern and boundary conditions for various mountain scale, repository scale, and drift scale models. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.2 Section 2.3.5
01-02 Repository Layout	FEP 1.1.07.00.0A – Repository Design FEP 1.2.04.03.0A – Igneous intrusion into repository FEP 2.1.05.01.0A – Flow through seals (access ramps and ventilation shafts) (Excluded) FEP 2.1.08.04.0A – Condensation forms on roofs of drifts (drift-scale cold traps) FEP 2.1.08.04.0B – Condensation forms at repository edges (repository-scale cold traps) FEP 2.1.08.09.0A – Saturated flow in the EBS (Excluded) FEP 2.1.11.03.0A – Exothermic reactions in the EBS (Excluded) FEP 2.1.13.02.0A – Radiation damage in EBS (Excluded)	Supports spatial domain of concern and boundary conditions for various mountain scale, repository scale, and drift scale models. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.3 Section 2.3.5 Section 2.3.11

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
01-03 Repository Geologic Location	FEP 1.1.01.01.0A – Open site investigation boreholes (Excluded) FEP 1.2.03.02.0B – Seismic-induced rockfall damages EBS components (Excluded) FEP 1.2.03.02.0C – Seismic-induced drift collapse damages EBS components FEP 2.2.01.02.0A – Thermally-induced stress changes in the near-field (Excluded) FEP 2.2.01.03.0A – Changes in fluid saturations in the excavation disturbed zone (Excluded) FEP 2.2.03.01.0A – Stratigraphy FEP 2.2.08.12.0A – Chemistry of water flowing into the drift FEP 2.1.03.10.0B – Advection of liquids and solids through cracks in the drip shield (Excluded)	Supports spatial domain of concern and boundary conditions for various mountain scale, repository scale, and drift scale models. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.5 Section 2.3.6
01-04 Repository Elevation-Standoff from Water Table	FEP 2.1.08.12.0A – Induced hydrologic changes in invert (Excluded) FEP 2.2.10.04.0A – Thermal-mechanical stresses alter characteristics of fractures near repository (Excluded) FEP 2.2.11.01.0A – Gas effects in the SZ (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.3 Section 2.3.11
01-05 Repository Standoff from Quaternary Fault	FEP 1.2.02.03.0A – Fault displacement damages EBS components FEP 2.2.07.05.0A – Flow in the UZ from episodic infiltration (Excluded)	Supports spatial domain of concern and boundary conditions for various mountain scale, repository scale, and drift scale models. Supports basis for FEP exclusion.	Section 2.2 Section 2.3.3 Section 2.3.4

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
01-06 Repository Elevation - Overburden Thickness	FEP 1.2.02.03.0A – Fault displacement damages EBS components FEP 1.2.07.01.0A – Erosion / denudation (Excluded) FEP 1.4.03.00.0A – Unintrusive site investigation (Excluded) FEP 1.4.11.00.0A – Explosions and crashes (human activities) (Excluded) FEP 1.5.01.01.0A – Meteorite Impact (Excluded) FEP 1.5.01.02.0A – Extraterrestrial events (Excluded) FEP 2.3.09.01.0A – Animal Burrowing / Intrusion (Excluded)	Supports spatial domain of concern and boundary conditions for various mountain scale, repository scale, and drift scale models. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4
01-07 Repository Standoff from Perched Water	FEP 2.2.06.03.0A – Seismic activity alters perched water zones (Excluded)	Supports basis for FEP exclusion	Section 2.2 Section 2.3.4
01-08 Orientation of Emplacement Drifts	FEP 2.1.07.01.0A – Rockfall (Excluded) FEP 2.1.07.02.0A – Drift Collapse (Excluded)	Supports basis for FEPs exclusion	Section 2.2 Section 2.3.4
01-09 Excavation Methods	FEP 1.1.02.00.0A – Chemical effects of excavation and construction in EBS (Excluded) FEP 1.1.02.00.0B – Mechanical effects of excavation and construction in EBS (Excluded) FEP 2.1.07.01.0A – Rockfall (Excluded) FEP 2.2.01.01.0A – Mechanical effects of excavation and construction in the near field	Supports the basis for performance assessment initial conditions Supports basis for FEPs exclusion	Section 2.2 Section 2.3.3 Section 2.3.4 Section 2.3.11

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
01-10 Emplacement Drift Configuration	FEP 1.1.02.00.0B – Mechanical effects of excavation and construction in EBS (Excluded) FEP 1.1.07.00.0A – Repository Design FEP 2.1.07.01.0A – Rockfall (Excluded) FEP 2.1.07.06.0A – Floor buckling (Excluded) FEP 2.1.11.10.0A – Thermal effects on transport in EBS (Excluded) FEP 2.2.06.04.0A – Effects of subsidence (Excluded) FEP 2.2.07.20.0A – Flow diversion around repository drifts	Supports spatial domain of concern and boundary conditions for various repository scale and drift scale models. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.3 Section 2.3.4 Section 2.3.5 Section 2.3.11
01-11 Emplacement Drift Gradient	FEP 2.1.08.12.0A – Induced hydrologic changes in invert (Excluded)	Supports basis for FEP exclusion.	Section 2.2
01-12 Non-Emplacement Opening Gradient	FEP 2.1.08.12.0A – Induced hydrologic changes in invert (Excluded)	Supports basis for FEP exclusion.	Section 2.2
01-13 Emplacement Drift Spacing	FEP 2.1.08.11.0A – Repository resaturation due to waste cooling FEP 2.2.06.04.0A – Effects of subsidence (Excluded) FEP 2.2.07.10.0A – Condensation zone forms around drifts FEP 2.2.07.20.0A – Flow diversion around repository drifts FEP 2.2.10.01.0A – Repository-induced thermal effects on flow in the UZ (Excluded)	Supports spatial domain of concern and boundary conditions for various repository scale and drift scale models. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.2 Section 2.3.3
01-14 Verification of Design Rock Properties	FEP 2.1.07.01.0A – Rockfall (Excluded) FEP 2.1.07.02.0A – Drift Collapse (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
01-15 Design of Ground Support System	FEP 1.1.01.01.0B – Influx through holes drilled in drift wall or crown (Excluded) FEP 2.1.06.01.0A – Chemical effects of rock reinforcement and cementitious materials in EBS (Excluded) FEP 2.1.06.02.0A – Mechanical effects of rock reinforcement materials in EBS (Excluded) FEP 2.1.06.04.0A – Flow through rock reinforcement materials in EBS (Excluded) FEP 2.1.07.01.0A – Rockfall (Excluded) FEP 2.1.07.02.0A – Drift Collapse (Excluded) FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded) FEP 2.1.09.17.0A – Formation of pseudo-colloids (corrosion product) in EBS FEP 2.2.01.01.0B – Chemical effects of excavation and construction in the near-field (Excluded) FEP 2.2.08.03.0B – Geotechnical interactions and evolution in the UZ (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.2 Section 2.3.3 Section 2.3.4 Section 2.3.5 Section 2.3.7 Section 2.3.8
01-16 Air Circulation through Ground Support	FEP 1.1.01.01.0B – Influx through holes drilled in drift wall or crown (Excluded) FEP 2.1.06.04.0A – Flow through rock reinforcement materials in EBS (Excluded) FEP 2.1.07.01.0A – Rockfall (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.3 Section 2.3.4 Section 2.3.5
01-17 Emplacement Drift Ground Support	FEP 2.1.06.02.0A – Mechanical effects of rock reinforcement materials in EBS (Excluded) FEP 2.1.07.01.0A – Rockfall (Excluded) FEP 2.1.07.02.0A – Drift Collapse (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.5

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
01-18 Unheated Drift Length	FEP 2.1.06.01.0A – Chemical effects of rock reinforcement and cementitious materials in EBS (Excluded) FEP 2.1.08.04.0A – Condensation forms on roofs of drifts (drift-scale cold traps) FEP 2.1.08.04.0B – Condensation forms at repository edges (repository-scale cold traps)	Supports the basis for performance assessment initial and boundary conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.5
01-19 Flood Protection	FEP 1.1.02.01.0A – Site flooding (during construction and operation) (Excluded) FEP 2.1.05.01.0A – Flow through seals (access ramps and ventilation shafts) (Excluded)	Supports basis for FEPs exclusion.	Section 2.2
01-20 Repository Standoff from Paintbrush Nonwelded Hydrogeologic Unit	FEP 2.2.10.05.0A - Thermo-Mechanical Stresses Alter Characteristics of Rocks above and below the Repository (Excluded)* FEP 2.2.10.06.0A - Thermo-Chemical Alteration in the UZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution) (Excluded)*	Supports basis for FEP exclusion	Section 2.2
01-21 Minimum Thickness of the Paintbrush Nonwelded Hydrogeologic Unit above the Repository	FEP 2.2.07.05.0A - Flow in the UZ from Episodic Infiltration (Excluded)*	Supports basis for FEP exclusion	Section 2.2
01-22 Repository Standoff from Calico Hills Nonwelded Hydrogeologic Unit	FEP 2.2.10.07.0A - Thermo-Chemical Alteration of the Calico Hills Unit (Excluded)* FEP 2.2.10.14.0A - Mineralogic Dehydration Reactions (Excluded)*	Supports basis for FEP exclusion	Section 2.2

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
02-01 As-Emplaced Waste Configuration	FEP 1.1.09.00.0A – Schedule and Planning· FEP 1.2.03.02.0A Seismic-Induced Rockfall Damages EBS Components FEP 2.1.06.05.0B Mechanical Degradation of Emplacement Pallet (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.09.09.0A – Electrochemical Effects in EBS (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEP exclusion.	Section 2.2 Section 2.3.4
02-02 As-Emplaced Waste Package-Drip Shield Configuration	FEP 1.2.03.02.0A – Seismic ground motion damages EBS components FEP 1.2.03.02.0B – Seismic-induced rockfall damages EBS components (Excluded) FEP 2.1.03.07.0B – Mechanical impact on drip shield (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.07.01.0A – Rockfall (Excluded) FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded)	Supports the basis for performance assessment initial and boundary conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
02-03 Committed Materials	FEP 1.1.02.00.0A – Chemical effects of excavation and construction in EBS (Excluded) FEP 1.1.02.03.0A – Undesirable materials left (Excluded) FEP 1.1.08.00.0A – Inadequate quality control and deviations from design (Excluded) FEP 2.1.05.01.0A – Flow through seals (access ramps and ventilation shafts) (Excluded) FEP 2.1.06.01.0A – Chemical effects of rock reinforcement and cementitious materials in EBS (Excluded) FEP 2.1.06.02.0A – Mechanical effects of rock reinforcement materials in EBS (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.09.01.0A – Chemical characteristics of water in drifts FEP 2.1.09.02.0A – Chemical Interaction with Corrosion Products FEP 2.1.09.17.0A – Formation of pseudo-colloids (corrosion product) in EBS FEP 2.1.09.28.0A – Localized Corrosion on Waste Package Outer Surface Due to Deliquescence (Excluded) FEP 2.1.12.04.0A – Gas generation (CO_2, CH_4, H_2S) from microbial degradation (Excluded) FEP 2.2.01.01.0B – Chemical effects of excavation and construction in the near-field (Excluded)	Supports the basis for performance assessment initial and boundary conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.5 Section 2.3.7

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
02-04 Invert and EBS Components in Situ Stress and Thermal Response	FEP 2.1.06.05.0B – Mechanical degradation of invert (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.11.07.0A – Thermal expansion / stress of in-drift EBS components (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.11
02-05 EBS In-Drift Materials Interactions	FEP 2.1.03.04.0A - Hydride Cracking of Waste Packages (Excluded) FEP 2.1.03.04.0B - Hydride Cracking of Drip Shields (Excluded) FEP 2.1.06.07.0A – Chemical effects at EBS component interfaces (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.09.02.0A – Chemical interaction with corrosion products FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.7
02-06 EBS Material Interactions—Copper	FEP 2.1.03.09.0A – Copper corrosion in EBS (Excluded) FEP 2.1.09.02.0A – Chemical interaction with corrosion products	Supports the basis for performance assessment initial conditions. Supports basis for FEP exclusion.	Section 2.2 Section 2.3.7
02-07 Emplacement Drift Invert Function	FEP 2.1.06.05.0B – Mechanical degradation of invert (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
02-08 Invert Materials	FEP 1.1.02.00.0A – Chemical effects of excavation and construction in EBS (Excluded) FEP 1.1.07.00.0A – Repository Design FEP 2.1.06.05.0B – Mechanical degradation of invert (Excluded) FEP 2.1.06.05.0C – Chemical degradation of emplacement pallet FEP 2.1.06.05.0D – Chemical degradation of invert (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.08.05.0A – Flow through invert FEP 2.1.09.02.0A – Chemical interaction with corrosion products FEP 2.1.09.03.0C – Volume increase of corrosion products impacts other EBS components (Excluded) FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.5 Section 2.3.7
02-09		Not used.	
02-10 Emplacement Drift Invert Configuration	FEP 2.1.06.05.0B – Mechanical degradation of invert (Excluded) FEP 2.1.09.03.0C – Volume increase of corrosion products impacts other EBS components (Excluded)	Supports basis for FEPs exclusion. Supports the basis for performance assessment initial and boundary conditions.	Section 2.2 Section 2.3.4

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
03-01 Waste Package Dimensions and Component Masses	FEP 1.1.07.00.0A – Repository Design FEP 1.1.08.00.0A – Inadequate quality control and deviations from design (Excluded) FEP 2.1.02.08.0A – Pyrophoricity from DSNF (Excluded) FEP 2.1.03.06.0A – Internal corrosion of waste packages prior to breach (Excluded) FEP 2.1.03.11.0A – Physical form of waste package and drip shield FEP 2.1.09.03.0B – Volume increase of corrosion products impacts waste package (Excluded) FEP 2.1.09.09.0A – Electrochemical Effects in EBS (Excluded) FEP 2.1.11.07.0A – Thermal expansion / stress of in-drift EBS components (Excluded) FEP 2.1.12.03.0A – Gas generation (H_2) from waste package corrosion (Excluded) FEP 2.1.13.01.0A – Radiolysis (Excluded)	Supports the basis for performance assessment initial and boundary conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.6 Section 2.3.7 Section 2.3.11
03-02 Waste Package Quantities	FEP 2.1.01.01.0A – Waste Inventory	Supports the basis for performance assessment initial conditions.	Section 2.3.7

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
03-03 Waste Package Outer Barrier Material Thickness	FEP 1.1.08.00.0A – Inadequate quality control and deviations from design (Excluded) FEP 1.2.03.02.0A – Seismic Ground Motion Damages EBS Components FEP 2.1.03.01.0A – General corrosion of waste packages FEP 2.1.03.03.0A – Localized corrosion of waste packages FEP 2.1.12.03.0A – Gas generation (H_2) from waste package corrosion (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.6
03-04 Waste Package Radial Gap	FEP 2.1.11.05.0A – Thermal expansion / stress of in-package EBS components (Excluded) FEP 2.1.11.07.0A – Thermal expansion/stress of in-drift EBS components (Excluded) FEP 2.1.03.07.0A – Mechanical impact on waste package (Excluded) FEP 2.1.09.03.0B – Volume increase of corrosion products impacts waste package (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4
03-05 Waste Package Longitudinal Gap	FEP 2.1.09.03.0B – Volume increase of corrosion products impacts waste package (Excluded) FEP 2.1.11.05.0A – Thermal expansion / stress of in-package EBS components (Excluded) FEP 2.1.11.07.0A – Thermal expansion/stress of in-drift EBS components (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4
03-06 Waste Package Internal Pressurization	FEP 2.1.03.07.0A – Mechanical impact on waste package (Excluded) FEP 2.1.12.02.0A – Gas generation (He) from waste form decay (Excluded) FEP 2.1.13.01.0A – Radiolysis (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.7

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
03-07 Waste Package Corrosion Allowance	FEP 1.2.03.02.0A - Seismic ground motion damages EBS components. FEP 2.1.03.01.0A – General corrosion of waste packages FEP 2.1.14.15.0A – In-package criticality (intact configuration) (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEP exclusion.	Section 2.2 Section 2.3.4 Section 2.3.6
03-08 Seismic Design of Waste Package	FEP 1.2.03.02.0A – Seismic ground motion damages EBS components FEP 2.1.06.05.0C – Chemical degradation of emplacement pallet	Supports the basis for performance assessment initial conditions.	Section 2.3.4
03-09 Waste Package Worst-Case Dose Rate	FEP 1.1.07.00.0A – Repository Design FEP 2.1.13.01.0A – Radiolysis (Excluded) FEP 2.1.13.02.0A – Radiation damage in EBS (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.7
03-10 Waste Package Design Basis Bounding Dose Rate	FEP 1.1.07.00.0A – Repository Design FEP 2.1.13.01.0A – Radiolysis (Excluded) FEP 2.1.13.02.0A – Radiation damage in EBS (Excluded) FEP 2.1.14.15.0A – In-package criticality (intact configuration) (Excluded)	Supports the basis for performance assessment initial and boundary conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.7
03-11 Waste Package Decay Heat	FEP 2.1.11.01.0A – Heat Generation in EBS	Supports the basis for performance assessment initial conditions.	Section 2.3.5
03-12 Waste Package Fabrication	FEP 2.1.03.08.0A – Early failure of waste packages	Supports bases for early failure event probability.	Section 2.2 Section 2.3.6
03-13 Waste Package Fabrication Weld Inspections	FEP 2.1.03.08.0A – Early failure of waste packages	Supports bases for early failure event probability.	Section 2.2 Section 2.3.6

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
03-14 Waste Package Welding Materials	FEP 2.1.03.02.0A – Stress corrosion cracking (SCC) of waste packages FEP 2.1.03.08.0A – Early failure of waste packages	Supports bases for early failure event probability.	Section 2.2 Section 2.3.6
03-15 Waste Package Fabrication Welding Flaws	FEP 2.1.03.02.0A – Stress corrosion cracking (SCC) of waste packages FEP 2.1.03.08.0A – Early failure of waste packages	Supports bases for early failure event probability.	Section 2.2 Section 2.3.6
03-16 Waste Package Annealing	FEP 2.1.03.02.0A – Stress corrosion cracking (SCC) of waste packages FEP 2.1.03.03.0A – Localized corrosion of waste packages FEP 2.1.03.08.0A – Early failure of waste packages FEP 2.1.03.10.0A – Advection of liquids and solids through cracks in the waste package (Excluded) FEP 2.1.11.06.0A – Thermal sensitization of waste packages (Excluded)	Supports bases for Early Failure Event Probability. Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.6 Section 2.3.7
03-17 Waste Package Closure	FEP 2.1.03.02.0A – Stress corrosion cracking (SCC) of waste packages FEP 2.1.03.03.0A – Localized corrosion of waste packages FEP 2.1.03.10.0A – Advection of liquids and solids through cracks in the waste package (Excluded) FEP 2.1.11.06.0A – Thermal sensitization of waste packages (Excluded) FEP 2.1.14.15.0A – In-package criticality (intact configuration) (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.6 Section 2.3.7
03-18 Waste Package Surface Marring Prior to Emplacement	FEP 2.1.03.02.0A – Stress corrosion cracking (SCC) of waste packages FEP 2.1.03.08.0A – Early Failure of Waste Packages	Supports the basis for performance assessment initial conditions.	Section 2.3.6

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
03-19 Waste Package Outer Corrosion Barrier Material Specifications	FEP 2.1.03.01.0A – General corrosion of waste packages FEP 2.1.03.03.0A – Localized corrosion of waste packages FEP 2.1.09.03.0B – Volume increase of corrosion products impacts waste package (Excluded) FEP 2.1.09.09.0A – Electrochemical Effects in EBS (Excluded) FEP 2.1.11.06.0A – Thermal sensitization of waste packages (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.6
03-20 Materials Contacting the Waste Package	FEP 2.1.09.09.0A – Electrochemical Effects in EBS (Excluded)	Supports basis for FEP exclusion.	Section 2.2
03-21 Waste Package Handling	FEP 2.1.03.08.0A – Early failure of waste packages	Supports bases for early failure event probability.	Section 2.2 Section 2.3.6
03-22 Waste Package Handling and Emplacement	FEP 1.1.03.01.0A – Error in waste emplacement (Excluded) FEP 2.1.03.08.0A – Early failure of waste packages	Supports bases for early failure event probability. Supports thermal analyses.	Section 2.2 Section 2.3.6
03-23 Waste Package Surface Finish	FEP 2.1.03.08.0A – Early failure of waste packages	Supports bases for early failure event probability.	Section 2.2 Section 2.3.6
03-24 Waste Package Surface Defects Damage Prior to Closure	FEP 2.1.03.08.0A – Early failure of waste packages FEP 2.1.03.07.0A – Mechanical impact on waste package (Excluded) FEP 2.1.07.01.0A – Rockfall (Excluded)	Supports the basis for performance assessment initial conditions.	Section 2.2 Section 2.3.4 Section 2.3.6
03-25		Not used.	

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
03-26 Waste Form Moisture Removal and Inerting	FEP 2.1.02.09.0A – Chemical Effects of Void Space in Waste Package FEP 2.1.03.06.0A – Internal Corrosion of Waste Packages Prior to Breach (Excluded) FEP 2.1.03.07.0A – Mechanical Impact on Waste Package (Excluded) FEP 2.1.13.01.0A – Radiolysis (Excluded) FEP 2.1.14.15.0A – In-Package Criticality (Intact Configuration) (Excluded) FEP 2.2.12.04.0A – Gas Generation (CO2, CH4, H2S) from Microbial Degradation (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.7
04-01 Loading of Waste Forms	FEP 2.1.03.06.0A – Internal corrosion of waste packages prior to breach (Excluded) FEP 2.1.11.07.0A – Thermal expansion / stress of in-drift EBS components (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.11
04-02 Handling of Uncanistered Spent Nuclear Fuel	FEP 2.1.02.02.0A CSNF degradation (alteration, dissolution, and radionuclide release)	Supports the basis for performance assessment initial conditions.	Section 2.3.7
04-03 Waste Form Commercial SNF Fuel Rod Maximum Burnup Limit	FEP 2.1.01.01.0A – Waste Inventory FEP 2.1.14.15.0A – In-package criticality (intact configuration) (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEP exclusion.	Section 2.2 Section 2.3.7

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
04-04 Waste Form Moisture Removal and Inerting	FEP 2.1.02.09.0A – Chemical effects of void space in waste package FEP 2.1.03.06.0A – Internal corrosion of waste packages prior to breach (Excluded) FEP 2.1.03.07.0A – Mechanical impact on waste package (Excluded) FEP 2.1.13.01.0A – Radiolysis (Excluded) FEP 2.1.14.15.0A – In-package criticality (intact configuration) (Excluded) FEP 2.2.12.04.0A – Gas Generation (CO_2, CH_4, H_2S) from microbial degradation (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.7
04-05 Cladding Temperature Limit - Waste Form		Not relevant because the performance assessment does not take credit for cladding performance.	
04-06 Maximum Temperature of HLW Glass Canisters - Waste Form	FEP 2.1.02.03.0A – HLW glass degradation (Alteration, Dissolution, and Radionuclide Release) FEP 2.1.02.06.0A – HLW Glass Recrystallization (Excluded)	Supports basis for HLW degradation rate in performance assessment. Supports basis for FEP exclusion.	Section 2.2 Section 2.3.7

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
04-07 Waste Package Capacities	FEP 2.1.01.01.0A – Waste Inventory FEP 2.1.01.02.0A – Interactions between co-located waste (Excluded) FEP 2.1.01.02.0B – Interactions between co-disposed waste FEP 2.1.01.03.0A – Heterogeneity of waste inventory FEP 2.1.02.01.0A – DSNF degradation (alteration, dissolution, and radionuclide release) FEP 2.1.02.09.0A – Chemical effects of void space in waste package FEP 2.1.02.28.0A – Grouping of DSNF waste types into categories FEP 2.1.02.29.0A – Flammable gas generation from DSNF (Excluded) FEP 2.1.03.06.0A – Internal corrosion of waste packages prior to breach (Excluded) FEP 2.1.09.01.0B – Chemical characteristics of water in waste package FEP 2.1.09.02.0A – Chemical interaction with corrosion products FEP 2.1.11.07.0A – Thermal expansion / stress of in-drift EBS components (Excluded) FEP 2.1.14.15.0A – In-package criticality (intact configuration) (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.7 Section 2.3.11
04-08 Handling of Waste Forms	FEP 2.1.02.01.0A – DSNF Degradation (Alteration, Dissolution, and Radionuclide Release) FEP 2.1.02.02.0A – CSNF Degradation (Alteration, Dissolution, and Radionuclide Release) FEP 2.1.02.03.0A – HLW glass degradation (Alteration, Dissolution, and Radionuclide Release)	Supports the basis for performance assessment initial conditions.	Section 2.3.7

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
04-09 Waste Package and TAD Canister Excluded Materials	FEP 2.1.02.10.0A – Organic / cellulosic materials in waste (Excluded) FEP 2.1.09.03.0B – Volume increase of corrosion products impacts waste package (Excluded) FEP 2.1.12.04.0A – Gas generation (CO_2, CH_4, H_2S) from microbial degradation (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4
05-01 Waste Package Handling and Emplacement	FEP 1.1.03.01.0A – Error in waste emplacement (Excluded) FEP 2.1.03.08.0A – Early failure of waste packages	Supports bases for early failure event probability. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.6
05-02 Waste Package Spacing	FEP 1.1.07.00.0A – Repository Design FEP 1.2.03.02.0A – Seismic Ground Motion Damages EBS Components	Supports the basis for performance assessment initial conditions.	Section 2.2 Section 2.3.4
05-03 Waste Package Thermal Limits	FEP 1.1.07.00.0A – Repository Design FEP 2.1.01.04.0A – Repository-scale spatial heterogeneity of emplaced waste FEP 2.1.08.03.0A – Repository dry-out due to waste heat FEP 2.1.11.06.0A – Thermal Sensitization of Waste Packages (Excluded) FEP 2.1.11.06.0B – Thermal Sensitization of Drip Shields (Excluded)	Supports the basis for performance assessment initial conditions.	Section 2.2 Section 2.3.5 Section 2.3.7

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
05-04 No Backfill in Emplacement Drifts	FEP 1.1.03.01.0B – Error in backfill emplacement (Excluded) FEP 2.1.04.01.0A – Flow in the backfill (Excluded) FEP 2.1.04.02.0A – Chemical properties and evolution of backfill (Excluded) FEP 2.1.04.03.0A – Erosion or dissolution of backfill (Excluded) FEP 2.1.04.04.0A – Thermal-mechanical effects of backfill (Excluded) FEP 2.1.04.05.0A – Thermal-mechanical properties and evolution of backfill (Excluded) FEP 2.1.4.09.0A – Radionuclide transport in backfill (Excluded) FEP 2.1.11.03.0A – Exothermic reactions in the EBS (Excluded) FEP 2.2.01.02.0B – Chemical changes in the near-field from backfill (Excluded)	Supports basis for FEPs exclusion.	Section 2.2
06-01 Duration of Ventilation Period	FEP 1.1.02.00.0A – Chemical effects of excavation and construction in EBS (Excluded) FEP 1.1.02.02.0A – Preclosure ventilation FEP 1.1.07.00.0A – Repository Design FEP 1.1.09.00.0A – Schedule and Planning FEP 2.1.11.01.0A – Heat generation in EBS FEP 2.2.01.03.0A – Changes in fluid saturations in the excavation disturbed zone (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.3 Section 2.3.5

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
06-02 Drift Wall Temperature	FEP 1.1.02.02.0A – Preclosure ventilation FEP 2.1.07.01.0A – Rockfall (Excluded) FEP 2.1.07.02.0A – Drift Collapse (Excluded) FEP 2.1.11.01.0A – Heat generation in EBS	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.3 Section 2.3.4 Section 2.3.5
06-03 Waste Package Temperature Limit	FEP 2.1.11.06.0A – Thermal sensitization of waste packages (Excluded)	Supports basis for FEP exclusion.	Section 2.2 Section 2.3.6
06-04 Cladding Temperature Limit - Ventilation		Not relevant because the performance assessment does not take credit for cladding performance.	
06-05 Maximum Temperature of HLW Glass Canisters - Ventilation	FEP 2.1.02.03.0A – HLW glass degradation (Alteration, Dissolution, and Radionuclide Release) FEP 2.1.02.06.0A – HLW Glass Recrystallization (Excluded)	Supports basis for HLW degradation rate in performance assessment. Supports basis for FEP exclusion.	Section 2.2 Section 2.3.7
06-06 Average Airflow Rate for Preclosure Ventilation Period	FEP 1.1.02.00.0A – Chemical Effects of Excavation and Construction in EBS (Excluded) FEP 1.1.02.02.0A – Preclosure Ventilation* FEP 2.1.11.01.0A – Heat Generation in EBS* FEP 2.2.10.13.0A – Repository-Induced Thermal Effects on Flow in the SZ (Excluded)*	Supports the basis for performance assessment initial conditions	Table 2.3.3-1 Table 2.3.5-1

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
07-01 Drip Shield Design	FEP 1.2.03.02.0B – Seismic-induced rockfall damages EBS components (Excluded) FEP 2.1.03.03.0B – Localized corrosion of drip shields (Excluded) FEP 2.1.03.04.0B – Hydride cracking of drip shields (Excluded) FEP 2.1.06.05.0B – Mechanical degradation of invert (Excluded) FEP 2.1.06.06.0A – Effects of drip shield on flow FEP 2.1.09.03.0C – Volume increase of corrosion products impacts other EBS components (Excluded) FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded) FEP 2.1.03.10.0B – Advection of liquids and solids through cracks in the Drip Shield (Excluded) FEP 2.1.03.11.0A – Physical form of waste package and drip shield	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.5 Section 2.3.6 Section 2.3.7
07-02 Drip Shield Design and Installation	FEP 1.1.07.00.0A – Repository Design FEP 2.1.06.06.0A – Effects of drip shield on flow	Supports the basis for performance assessment initial conditions.	Section 2.2 Section 2.3.5 Section 2.3.7
07-03		Not used.	

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
07-04 Drip Shield Materials and Thicknesses	FEP 1.1.07.00.0A – Repository Design FEP 1.2.03.02.0A – Seismic Ground Motion Damages EBS Components FEP 1.2.03.02.0B – Seismic-induced rockfall damages EBS components (Excluded) FEP 2.1.03.01.0B – General corrosion of drip shields FEP 2.1.03.03.0B – Localized corrosion of drip shields (Excluded) FEP 2.1.03.04.0B – Hydride cracking of drip shields (Excluded) FEP 2.1.03.05.0B – Microbially influenced corrosion (MIC) of drip shields (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.07.02.0A – Drift Collapse (Excluded) FEP 2.1.08.15.0A – Consolidation of EBS components (Excluded) FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded) FEP 2.1.09.28.0B – Localized corrosion on drip shield surfaces due to deliquescence (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.6
07-05		Not used.	
07-06		Not used.	

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
07-07 EBS Drip Shield / Emplacement Drift Invert Materials Interactions	FEP 1.1.07.00.0A – Repository Design FEP 2.1.03.04.0B – Hydride cracking of drip shields (Excluded) FEP 2.1.03.09.0A – Copper corrosion in EBS (Excluded) FEP 2.1.06.07.0A – Chemical effects at EBS component interfaces (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2
07-08 Drip Shield Seismic Performance	FEP 1.2.03.02.0A – Seismic Ground Motion Damages EBS Components FEP 2.1.03.02.0B – Stress corrosion cracking (SCC) of drip shields (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded)	Supports the basis for performance assessment initial conditions Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.6
07-09 Drip Shield Fabrication	FEP 2.1.03.08.0B – Early failure of drip shields	Supports bases for early failure event probability.	Section 2.2 Section 2.3.6
07-10 Drip Shield Fabrication Weld Inspections	FEP 2.1.03.08.0B – Early failure of drip shields	Supports bases for early failure event probability.	Section 2.2 Section 2.3.6
07-11 Drip Shield Fabrication Welding Flaws	FEP 2.1.03.08.0B – Early failure of drip shields	Supports bases for early failure event probability.	Section 2.2 Section 2.3.6
07-12 Drip Shield Fabrication Weld Materials	FEP 2.1.03.04.0B – Hydride cracking of drip shields (Excluded) FEP 2.1.03.08.0B – Early failure of drip shields	Supports bases for early failure event probability. Supports basis for FEP exclusion.	Section 2.2 Section 2.3.6

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
07-13 Drip Shield Heat Treatment	FEP 2.1.03.02.0B – Stress corrosion cracking (SCC) of drip shields (Excluded) FEP 2.1.03.10.0B – Advection of liquids and solids through cracks in the drip shield (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.6
07-14 Drip Shield Handling	FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.03.07.0A – Mechanical impact on waste package (Excluded) FEP 2.1.03.08.0B – Early failure of drip shields	Supports bases for early failure event probability. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.6
07-15 Drip Shield Thermal Expansion Constraint	FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.11.07.0A – Thermal expansion / stress of in-drift EBS components (Excluded)	Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.11
07-16 As-emplaced Waste Configuration - Waste Package / Drip Shield Clearance	FEP 1.2.03.02.0A – Seismic ground motion damages EBS components FEP 1.2.03.02.0B – Seismic-induced rockfall damages EBS components (Excluded)	Supports basis for FEP exclusion. Supports the basis for performance assessment initial conditions.	Section 2.2 Section 2.3.4
07-17		Not used.	

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
08-01 Emplacement Pallet Design	FEP 1.2.03.02.0B – Seismic-induced rockfall damages EBS components (Excluded) FEP 2.1.03.09.0A – Copper corrosion in EBS (Excluded) FEP 2.1.06.05.0A – Mechanical degradation of emplacement pallet (Excluded) FEP 2.1.06.05.0C – Chemical degradation of emplacement pallet FEP 2.1.06.07.0A – Chemical effects at EBS component interfaces (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.08.07.0A – Unsaturated flow in the EBS FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded) FEP 2.1.11.07.0A – Thermal expansion / stress of in-drift EBS components (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.5 Section 2.3.7 Section 2.3.11
08-02 Emplacement Pallet Function	FEP 2.1.03.09.0A – Copper corrosion in EBS (Excluded) FEP 2.1.06.05.0A – Mechanical degradation of emplacement pallet (Excluded) FEP 2.1.06.05.0C – Chemical degradation of emplacement pallet FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.08.07.0A – Unsaturated flow in the EBS FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4 Section 2.3.5 Section 2.3.7

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
08-03 Emplacement Pallet Fabrication and Corrosion Allowance	FEP 1.2.03.02.0A – Seismic ground motion damages EBS components FEP 2.1.03.04.0A – Hydride cracking of waste packages (Excluded) FEP 2.1.03.09.0A – Copper corrosion in EBS (Excluded) FEP 2.1.06.05.0A – Mechanical degradation of emplacement pallet (Excluded) FEP 2.1.06.05.0C – Chemical degradation of emplacement pallet FEP 2.1.06.07.0A – Chemical effects at EBS component interfaces (Excluded) FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded) FEP 2.1.09.09.0A – Electrochemical effects in EBS (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.4
08-04 EBS Materials Interactions - Emplacement Pallet Function	FEP 2.1.06.05.0C – Chemical Degradation of Emplacement Pallet FEP 2.1.06.07.0A – Chemical Effects at EBS Component Interfaces (Excluded) FEP 2.1.09.09.0A – Electrochemical Effects in EBS (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion	Section 2.2 Section 2.3.4
08-05 Waste Package and Emplacement Pallet Static Stresses	FEP 2.1.03.02.0A – Stress Corrosion Cracking (SCC) of waste packages FEP 2.1.06.05.0C – Chemical degradation of emplacement pallet FEP 2.1.06.07.0B – Mechanical effects at EBS component interfaces (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEP exclusion.	Section 2.2 Section 2.3.4 Section 2.3.6

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
09-01 Closure of Shafts and Ramps	FEP 1.1.03.01.0B – Error in backfill emplacement (Excluded) FEP 1.1.09.00.0A – Schedule and Planning FEP 2.1.04.01.0A – Flow in the backfill (Excluded) FEP 2.1.04.02.0A – Chemical properties and evolution of backfill (Excluded) FEP 2.1.04.03.0A – Erosion or dissolution of backfill (Excluded) FEP 2.1.04.04.0A – Thermal-mechanical effects of backfill (Excluded) FEP 2.1.04.05.0A – Thermal-mechanical properties and evolution of backfill (Excluded) FEP 2.1.04.09.0A – Radionuclide transport in backfill (Excluded) FEP 2.1.05.01.0A – Flow through seals (access ramps and ventilation shafts) (Excluded) FEP 2.1.05.02.0A – Radionuclide transport through seals (Excluded) FEP 2.1.05.03.0A – Degradation of seals (Excluded) FEP 2.2.01.02.0B – Chemical changes in the near-field from backfill (Excluded) FEP 2.3.09.01.0A – Animal burrowing / intrusion (Excluded)	Supports the basis for performance assessment initial conditions. Supports basis for FEPs exclusion.	Section 2.2
09-02		Not used.	
09-03 Closure of Boreholes	FEP 1.1.01.01.0A – Open site investigation boreholes (Excluded) FEP 1.1.11.00.0A – Monitoring of the repository (Excluded)	Supports basis for FEPs exclusion.	Section 2.2

Table 2.2-3. Repository Design Use in Performance Assessment (Continued)

Control Parameter	Representative FEPs Using Design/ Control Parameter	Control Parameter Use in Performance Assessment	Postclosure SAR Sections Discussing Representative FEPs
09-04 Reclamation of Lands Disturbed by Repository	FEP 1.2.07.01.0A – Erosion / denudation (Excluded) FEP 2.3.01.00.0A – Topography and morphology FEP 2.3.11.02.0A – Surface Runoff and Flooding FEP 2.3.11.03.0A – Infiltration and Recharge FEP 3.3.06.01.0A – Repository excavation (Excluded)	Supports the basis for performance assessment initial and boundary conditions. Supports basis for FEPs exclusion.	Section 2.2 Section 2.3.1 Section 2.3.2

NOTE: Retrievability (FEP 1.1.13.00.0A) is a high-level design requirement that has been applied to all appropriate design parameters. It is not listed explicitly in this table.

Source: SNL 2008a, Appendix A.

Table 2.2-4. Descriptions for Processes Analyzed for the System FEPs

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
0.1.02.00.0A Timescales of concern	This FEP addresses the timescales of concern over which the disposal system may present a significant health or environmental hazard.	The timescales of concern has been set by the NRC in proposed 10 CFR Part 63. Compliance with the individual protection standard after permanent closure (proposed 10 CFR 63.311) and the individual protection standard for human intrusion (proposed 10 CFR 63.321) must be demonstrated for the timescale of geologic stability. The period of geologic stability is defined at proposed 10 CFR 63.302 as “the time during which the variability of geologic characteristics and their future behavior in and around the Yucca Mountain site can be bounded, that is, they can be projected within a reasonable range of possibilities. This period is defined to end at 1 million years after disposal.” Compliance with the groundwater protection standard (10 CFR 63.331) must be demonstrated on a timescale of 10,000 years. Proposed 10 CFR 63.303(a) states that “Compliance is based upon the arithmetic mean of the projected doses from DOE’s performance assessments for the period within 10,000 years after disposal…” and proposed 10 CFR 63.303(b) states that “Compliance is based upon the median of the projected doses from DOE’s performance assessments for the period after 10,000 years of disposal and through the period of geologic stability…”
0.1.03.00.0A Spatial domain of concern	This FEP addresses the spatial domain of concern over which the disposal system may present a significant health or environmental hazard.	From a modeling perspective, the spatial domain of concern is a function of the scale of the analysis being performed. The extent of the spatial domain that is considered in different components of the TSPA model also depends on the phenomenon that is being considered. Individual model domains are described in the documentation of each component of the TSPA model and in individual model/analysis reports (AMRs). The spatial domain encompassed by the entire TSPA model extends vertically downwards from the land surface in the vicinity of the repository through the unsaturated zone, through the repository and into the saturated zone, and extends laterally away from the repository to the location of the RMEI. In the TSPA, for demonstrations of compliance with the individual protection standard after permanent closure (proposed 10 CFR 63.311) and the individual protection standard for human intrusion (proposed 10 CFR.321), the spatial domain in which there is a potential for a significant health hazard is primarily defined by the location of the RMEI. as specified at 10 CFR 63.312(a). The compliance location for the groundwater protection standards at 10 CFR 63.331 is the representative volume in the accessible environment, which is defined at 10 CFR 63.332(a). Therefore, the spatial domain over which the disposal system may present a significant health or environmental hazard extends to approximately 18 km in the direction of groundwater flow (generally to the south) and over the whole of the controlled area defined in 10 CFR 63.302. GI-Section 1, Figure 1-4 is a map of the area including the postclosure controlled area boundary.

Table 2.2-4. Descriptions for Processes Analyzed for the System FEPs (Continued)

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
0.1.09.00.0A Regulatory requirements and exclusions	This FEP addresses regulatory requirements and guidance specific to the Yucca Mountain repository.	Proposed 10 CFR Part 63 (70 FR 53313) contains the NRC licensing regulations that provide the requirements for Yucca Mountain repository design, construction, operation, and preclosure and postclosure performance. Proposed 10 CFR Part 63 (70 FR 53313) requires performance assessments to demonstrate compliance with these postclosure radiation protection standards: individual protection standard of proposed 10 CFR 63.311 (70 FR 53313), the human intrusion individual protection standard of proposed 10 CFR 63.321 (70 FR 53313), and groundwater protection standards of 10 CFR 63.331. The TSPA is the tool used to implement these performance assessments. Proposed 10 CFR 63.114 and proposed 10 CFR 63.342 (70 FR 53313) provide the criteria for the screening of features, events and processes (FEPs) to determine whether the FEP will be excluded from the TSPA model on the basis of either low probability, low consequence, or by regulation, or included in the TSPA. Included FEPs are used to construct the scenario classes that are evaluated by the TSPA. NUREG-1804 provides guidance (Acceptance Criteria) to the NRC staff on how to assess the completeness and adequacy of the information in DOE's license application. DOE has provided information in the license application to address the Acceptance Criteria. Therefore, although NUREG-1804 is not a regulatory requirement, the Yucca Mountain Project has treated the Acceptance Criteria as important guidance for development of process models. There are other NUREGs relevant to and adopted by the Yucca Mountain Repository Project, including, but not limited to, for example, NUREG-1563, *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program* (Kotra et al. 1996); NUREG-1297, *Peer Review for High-Level Nuclear Waste Repositories: Generic Technical Position* (Altman et al. 1988a); and NUREG-1298, *Qualification of Existing Data for High-Level Nuclear Waste Repositories: Generic Technical Position* (Altman et al. 1988b). The use of NUREG-1563, *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program* (Kotra et al. 1996), is described in Section 5.4. Proposed 10 CFR Part 63 requires a Quality Assurance program. As indicated in Section 5.1, the Office of Civilian Radioactive Waste Management *Quality Assurance Requirements and Description* (DOE 2007) describes the requirements of the Quality Assurance Program that apply to activities at the Yucca Mountain repository.

Table 2.2-4. Descriptions for Processes Analyzed for the System FEPs (Continued)

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
0.1.10.00.0A Model and data issues	This FEP addresses issues related to modeling of the disposal system. Model and data issues are general (i.e., methodological) issues affecting the modeling process and data usage. Model issues include the approach and assumptions associated with the selection of conceptual models, the mathematical implementation of conceptual models, model geometry and dimensionality, models of coupled processes, and boundary and initial conditions. Data issues include the derivation of data values, correlations, and dependence of parameter selection on model scale.	Section 2.3 presents the technical bases for models and model abstractions that are used as a basis for the development of parameter inputs to the TSPA. Sections 2.3.1 to 2.3.11 describe the physical setting, coupled processes (i.e., thermal, chemical, mechanical, and hydrologic) in the repository system, processes in the biosphere that determine exposure to radionuclides and resultant doses, and disruptive events. Sections 2.3.1 to 2.3.11 cover characterization of the processes, analytical models of the processes, and uncertainty of the characterization of the data and parameters used in the models. In addition, Section 2.3 includes discussion of uncertainty. These discussions generally mirror the acceptance criteria set forth in NUREG-1804 and appear in the following order: • Conceptual description of the model (NUREG-1804, Acceptance Criterion 1) • Data and data uncertainty (NUREG-1804, Acceptance Criteria 2 and 3) • Model and model uncertainty (NUREG-1804, Acceptance Criterion 4) • Model abstraction and validation (NUREG-1804, Acceptance Criterion 5). Section 2.4 presents a discussion of the TSPA model and the analytical results that demonstrate compliance with the performance objectives of 10 CFR 63.113(b), (c), and (d) for individual protection, groundwater protection, and human intrusion, respectively. Section 2.4.1 describes (1) the TSPA model and discusses its overall design; (2) structure of the models that provide values, ranges, and response surfaces to the TSPA model for the nominal scenario; (3) treatment of disruptive events; (4) use of mean annual dose; and (5) treatment of uncertainty in the TSPA. Section 2.4.1 also provides a summary discussion of the integration within the TSPA of the individual abstraction models presented in Section 2.3. Methodology—The general performance assessment process adopted by the DOE follows the methodology developed by Cranwell et al. (1990, Sections 2 and 3). Over time, the methodology has been enhanced, including input from the NRC, and applied to numerous projects by various international organizations involved in radioactive waste management. Previous performance assessments and related supplemental analyses of the performance of the Yucca Mountain repository were conducted to meet various regulatory milestones, following the publication of the Nuclear Waste Policy Amendments Act of 1987, Public Law No. 100-203. The Yucca Mountain performance assessments have been iterative, with each succeeding performance assessment building on and extending the scope and results of the previous performance assessments by incorporating both an improved understanding of the processes affecting performance and, through additional field observations and laboratory analyses, better identification and quantification of the parameters used in the TSPAs. Discussions of the performance assessment methodology are included in Sections 2, 2.2, 2.3, and 2.4.

Table 2.2-4. Descriptions for Processes Analyzed for the System FEPs (Continued)

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
1.1.07.00.0A Repository design	This FEP addresses the consideration of the design of the repository and the ways in which the design contributes to long term performance. The performance assessment must account for design features, material characteristics, and the ways in which the design influences the evolution of the in drift environment.	Repository design is one of the bases for the models used for the performance assessments. Particularly relevant to this FEP are the model components for waste package and drip shield degradation, waste form degradation and mobilization, and EBS flow and transport. These model components take into account the physical dimensions, material characteristics, and evolution of the in-drift environment, all of which stem directly from design considerations. The design elements are included in the TSPA as parameters that define the physical dimensions, characteristics, and long-term behavior of the waste form, waste packages, and EBS. Table 2.2-3 identifies relevant parameters from the design and summarizes how those parameters are used in the performance assessment. Section 1.3.4 provides a detailed description of the emplacement areas of the subsurface facility including emplacement drifts, invert, excavation methods, ground support system, waste package pallet, and drip shield. Section 1.5.1 describes the waste forms that are analyzed in the performance assessments. Section 1.5.2 describes the waste package and its internal components that are analyzed in the performance assessments.
1.1.09.00.0A Schedule and Planning	This FEP addresses the sequences of events and activities occurring during construction, operation, and closure of the repository. Deviations from the design, construction, or waste emplacement schedule may affect the long-term performance of the disposal system.	The proposed schedules for construction, receipt, and emplacement of wastes are described in GI-Section 2.1. Scheduling and planning are components of the process implemented to achieve the expected repository postclosure conditions. The subsurface facilities are planned to be constructed in phases and the development of the subsurface facilities will proceed while emplacement operations are conducted in the completed drifts. The schedule for waste emplacement and planned subsurface ventilation will affect the radionuclide inventories and Thermal-hydrologic conditions at the time of repository closure. In particular, conditions at closure will depend on the implementation of design requirements for subsurface facilities and their ventilation, sealing and closure (SNL 2007m), and for waste emplacement (SNL 2007n). Modifications and deviations from the design for construction, operation, and closure of the repository are subject to regulatory requirements and review that address deliberate changes and modifications. The manner in which the DOE must address changes, and by which the NRC is informed of the changes, is codified at 10 CFR 63.44. After the NRC authorizes construction of the repository, changes to the repository design or procedures as described in the Safety Analysis Report (SAR) will be subject to the requirements of 10 CFR 63.44, Changes, tests, and experiments, as well as any specific license conditions imposed in accordance with 10 CFR 63.32, Conditions of construction authorization, 10 CFR 63.42, Conditions of license, or 10 CFR 63.43, License specifications. Note that deviations from design as a result of inadequate quality control during repository construction, operation, and closure is addressed in excluded FEP 1.1.08.00.0A, Inadequate quality control and deviations from design.

Table 2.2-4. Descriptions for Processes Analyzed for the System FEPs (Continued)

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
1.1.13.00.0A Retrievability	This FEP addresses design, emplacement, operational, or administrative measures that might be applied or considered to enable or ease retrieval of waste. There may be a requirement to retrieve all or part of the waste stored in the repository, for example, to recover valuable fissile materials or to replace defective waste packages.	Retrievability is a performance objective of the repository as specified at 10 CFR 63.111(e). As described in Section 1.3.2.4, the subsurface facility preserves the option to retrieve any or all of the emplaced waste starting at any time up to 50 years after initiation of waste emplacement. The repository ground support, ventilation, rail, and other support systems are designed to remain effective for up to 100 years after the initiation of waste emplacement such that the occurrence of rockfall or anticipated off-normal events do not preclude retrieval. The regulation specifies that the repository be designed in such a way that it preserves "…the option of waste retrieval throughout the period during which wastes are being emplaced…so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated…" (10 CFR 63.111(e)(1). This precludes further FEP consideration for retrieval past 50 years after the start of waste emplacement. Postclosure retrieval of wastes or other repository-system components for resource recovery was addressed by the NRC in the supplementary information for 10 CFR Part 63, p. 55743, Section III, Public Comments and Response, 2.2 Retrievability, Issue 2). To wit: As for longer retrieval periods (>50 years)…the Commission has previously noted that its retrieval provision is not intended to facilitate recovery. Waste retrieval is intended to be an unusual event only to be undertaken to protect public health and safety. Regardless, the repository design is part of the basis of the postclosure evaluation, and aspects of the repository design related to waste retrievability are, therefore, considered as part of the basis for the TSPA modeling and are included, as noted in included FEP 1.1.07.00.0A, Repository design.

Source: SNL 2008a.

Table 2.2-5. Complete Listing of FEPs Considered

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
0.1.02.00.0A	Timescales of Concern	This FEP addresses the timescales of concern over which the disposal system may present a significant health or environmental hazard.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.2-4
0.1.03.00.0A	Spacial Domain of Concern	This FEP addresses the spatial domain of concern over which the disposal system may present a significant health or environmental hazard.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.2-4
0.1.09.00.0A	Regulatory Requirements and Exclusions	This FEP addresses regulatory requirements and guidance specific to the Yucca Mountain repository.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.2-4
0.1.10.00.0A	Model and Data Issues	This FEP addresses issues related to modeling of the disposal system. Model and data issues are general (i.e., methodological) issues affecting the modeling process and data usage. Model issues include the approach and assumptions associated with the selection of conceptual models, the mathematical implementation of conceptual models, model geometry and dimensionality, models of coupled processes, and boundary and initial conditions. Data issues include the derivation of data values, correlations, and dependence of parameter selection on model scale.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.2-4
1.1.01.01.0A	Open Site Investigation Boreholes	Site investigation boreholes that have been left open, degraded, improperly sealed, or reopened, could modify flow and transport properties and produce enhanced pathways between the surface and the repository.	Excluded low consequence	See Footnote
1.1.01.01.0B	Influx Through Holes Drilled in Drift Wall or Crown	Holes may be drilled through the drift walls or crown for a variety of reasons including, but not limited to, rock bolt and ground support, monitoring and testing, or construction related activities. These openings may promote flow or seepage into the drifts and onto the waste packages.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.1.02.00.0A	Chemical Effects of Excavation and Construction in EBS	Chemical effects associated with excavation and construction of the underground regions of the repository may affect the long-term behavior of the natural and engineered barriers. Excavation-related effects include chemical changes to the rock and incoming groundwater due to explosives residue. Excavation and other construction activities could also directly cause groundwater chemistry changes within the tunnel due to contaminants such as diesel exhaust or other organic contaminants. Finally, oxidizing water introduced into the repository during excavation and construction could impact repository conditions and performance.	Excluded low consequence	See Footnote
1.1.02.00.0B	Mechanical Effects of Excavation and Construction in EBS	Mechanical effects associated with excavation and construction of the underground regions of the repository may affect the long-term behavior of the natural and engineered barriers. Excavation-related effects include changes to rock properties due to boring and blasting.	Excluded low consequence	See Footnote
1.1.02.01.0A	Site Flooding (During Construction and Operation)	Flooding of the site during construction and operation could introduce water into the underground tunnels, which could affect the long-term performance of the repository.	Excluded low consequence	See Footnote
1.1.02.02.0A	Preclosure Ventilation	The duration of preclosure ventilation acts together with waste package spacing (as per design) to control the extent of the boiling front (zone of reduced water content).	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2
1.1.02.03.0A	Undesirable Materials Left	During construction and preclosure operation of the repository, unwanted materials might be left in the vicinity of the radioactive waste. These materials could, to some extent, affect many long-term processes in the repository from waste package corrosion to radionuclide transport mechanisms.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.1.03.01.0A	Error in Waste Emplacement	Deviations from the design and/or errors in waste emplacement could affect long-term performance of the repository. A specific example of such an error would be erroneously emplacing the waste packages in a saturated or wet zone of the repository. Errors of this type would impact repository performance by affecting waste package corrosion and radionuclide transport.	Excluded low consequence	See Footnote
1.1.03.01.0B	Error in Backfill Emplacement	Deviations from the design and/or errors in the backfill emplacement could affect long-term performance of the repository.	Excluded low consequence	See Footnote
1.1.04.01.0A	Incomplete Closure	Disintegration of society could result in incomplete closure, sealing, and decommissioning of the disposal vault.	Excluded by Regulation	See Footnote
1.1.05.00.0A	Records and Markers for the Repository	This FEP addresses the retention of records of the contents of the repository and markers constructed to inform future humans of the location and contents of the repository. Performance assessments must consider the potential effects of human activities that might take place within the controlled area at a future time when institutional controls and/or knowledge of the presence of a repository cannot be assumed.	Excluded by Regulation	See Footnote
1.1.07.00.0A	Repository Design	This FEP addresses the consideration of the design of the repository and the ways in which the design contributes to long-term performance. The performance assessment must account for design features, material characteristics, and the ways in which the design influences the evolution of the in-drift environment.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.2-4
1.1.08.00.0A	Inadequate Quality Control and Deviations from Design	This FEP addresses issues related to inadequate quality assurance and control procedures and inadequate testing during the design, construction, and operation of the repository. It also includes inadequacy in the manufacture of the waste forms, waste packages, and engineered features. Lack of quality control could result in a poorly designed repository, unmodeled design features, deviations from design, material defects, faulty waste package fabrication, and faulty or nondesign standard construction. All of these may lead to reduction in the effectiveness of the engineered barriers.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.1.09.00.0A	Schedule and Planning	This FEP addresses the sequences of events and activities occurring during construction, operation, and closure of the repository. Deviations from the design, construction, or waste emplacement schedule may affect the long-term performance of the disposal system.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.2-4
1.1.10.00.0A	Administrative Control of the Repository Site	Administrative control can reduce the potential for detrimental or unplanned human activities within the controlled area that could inadvertently cause or accelerate the release of radioactive material.	Excluded by Regulation	See Footnote
1.1.11.00.0A	Monitoring of the Repository	Monitoring that is carried out during or after operations, for either operational safety or verification of long-term performance, has the potential to detrimentally affect long-term performance. For example, monitoring boreholes could provide enhanced pathways between the surface and the repository.	Excluded low consequence	See Footnote
1.1.12.01.0A	Accidents and Unplanned Events During Construction and Operation	The long-term performance of the disposal system might be seriously affected by unplanned or improper activities that take place during construction, operation, and closure of the repository.	Excluded by Regulation	See Footnote
1.1.13.00.0A	Retrievability	This FEP addresses design, emplacement, operational, or administrative measures that might be applied or considered to enable or ease retrieval of waste. There may be a requirement to retrieve all or part of the waste stored in the repository, for example, to recover valuable fissile materials or to replace defective waste packages.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.2-4
1.2.01.01.0A	Tectonic Activity – Large Scale	Large-scale tectonic activity, such as regional uplift, subsidence, folding, mountain building, or other processes related to plate movements, could affect repository performance by altering the physical and Thermal-hydrologic properties of the geosphere.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.2.02.01.0A	Fractures	Groundwater flow in the Yucca Mountain region and transport of any released radionuclides may take place along fractures. The rate of flow and the extent of transport in fractures are influenced by characteristics such as orientation, aperture, asperity, fracture length, connectivity, and the nature of any linings or infills.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.1-1 Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-2 Table 2.3.7-1 Table 2.3.8-1 Table 2.3.9-1
1.2.02.02.0A	Faults	Numerous faults of various sizes have been noted in the Yucca Mountain region and specifically in the repository area. Faults may represent an alteration of the rock permeability and continuity of the rock mass, an alteration or short-circuiting of the flow paths and flow distributions close to the repository, and/or unexpected pathways through the repository.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.3-1 Table 2.3.8-1 Table 2.3.9-1
1.2.02.03.0A	Fault Displacement Damages EBS Components	Movement of a fault that intersects drifts within the repository may cause the EBS components to experience related movement or displacement. Repository performance may be degraded by such occurrences as tilting of components, component-to-component contact, or drip shield separation. Fault displacement could cause a failure as significant as shearing of drip shields and waste packages by virtue of the relative offset across the fault, or as extreme as exhumation of the waste to the surface.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.4-1
1.2.03.02.0A	Seismic Ground Motion Damages EBS Components	Seismic activity that causes repeated vibration of the EBS components (drip shield, waste package, pallet, and invert) could result in severe disruption of the drip shields and waste packages, through vibration damage or through contact between EBS components. Such damage mechanisms could lead to degraded performance.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.4-1
1.2.03.02.0B	Seismic-Induced Rockfall Damages EBS Components	Seismic activity could produce jointed-rock motion and/or changes in rock stress leading to enhanced rockfall that could impact drip shields, waste packages, or other EBS components.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.2.03.02.0C	Seismic-Induced Drift Collapse Damages EBS Components	Seismic activity could produce jointed-rock motion and/or changes in rock stress leading to enhanced drift collapse that could impact drip shields, waste packages, or other EBS components. Possible effects include both dynamic and static loading.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.4-1
1.2.03.02.0D	Seismic-Induced Drift Collapse Alters In-Drift Thermal-hydrology	Seismic activity could produce jointed-rock motion and/or changes in rock stress leading to enhanced drift collapse and/or rubble infill throughout part or all of the drifts. Drift collapse could impact flow pathways and condensation within the EBS, mechanisms for water contact with EBS components, and thermal properties within the EBS.	Included 10 CFR 63.311(proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.4-1
1.2.03.02.0E	Seismic-Induced Drift Collapse Alters In-Drift Chemistry	Seismic activity could produce jointed-rock motion and/or changes in rock stress leading to enhanced drift collapse and/or rubble infill throughout part or all of the drifts. Drift collapse, and the associated changes in seepage and in-drift thermal-hydrology could impact in-drift chemistry.	Excluded low consequence	See Footnote
1.2.03.03.0A	Seismicity Associated with Igneous Activity	Seismicity associated with future igneous activity in the Yucca Mountain region may affect repository performance.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.4-1
1.2.04.02.0A	Igneous Activity Changes Rock Properties	Igneous activity near the underground facility may cause extreme changes in rock stress and the thermal regime, and may lead to rock deformation, including activation, creation, and sealing of faults and fractures. This may cause changes in the rock hydrologic and mineralogic properties. Permeabilities of dikes and sills and the heated regions immediately around them can differ from those of country rock. Mineral alterations can also change the chemical response of the host rock to contaminants.	Excluded low consequence	See Footnote
1.2.04.03.0A	Igneous Intrusion into Repository	Magma from an igneous intrusion may flow into the drifts and extend over a large portion of the repository site, forming a sill, dike, or dike swarm, depending on the stress conditions. This intrusion could involve multiple drifts. The sill could be limited to the drifts or a continuous sill could form along the plane of the repository, bridging between adjacent drifts.	Included 10 CFR 63.311 (proposed)	Table 2.3.3-1 Table 2.3.11-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.2.04.04.0A	Igneous Intrusion Interacts with EBS Components	An igneous intrusion in the form of a dike may occur through the repository, intersecting the repository drifts, resulting in magma, pyroclastic debris, and volcanic gases entering the drift and interacting with the EBS components (drip shields, waste packages, pallet, and invert). This could lead to accelerated drip shield and waste package failure (e.g., attack by magmatic volatiles, damage by flowing or fragmented magma, thermal effects) and dissolution or volatilization of waste.	Included 10 CFR 63.311 (proposed)	Table 2.3.11-1
1.2.04.04.0B	Chemical Effects of Magma and Magmatic Volatiles	An igneous intrusion into the repository may be accompanied by the release of magmatic volatiles. The volatiles may affect in-drift chemistry (potentially leading to increased waste package corrosion), or may be absorbed by the host rock, where they could change the chemistry of the water seeping back into the drift following the intrusive event. Seepage water chemistry following magma cooling could also be affected by flowing through and interacting with the intruded basalt.	Included 10 CFR 63.311 (proposed)	Table 2.3.11-1
1.2.04.05.0A	Magma or Pyroclastic Base Surge Transports Waste	FEP Description: As a result of an igneous intrusion, extrusive processes may result in a pyroclastic density current (base surge), effusive lava flows, and/or development of a volcanic cone at the land surface. Some of the waste (entrained, dissolved, or volatized) could then be transported away from the repository. Of most concern is transport directly along the land surface to the RMEI.	Excluded low consequence	See Footnote
1.2.04.06.0A	Eruptive Conduit to Surface Intersects Repository	As a result of an igneous intrusion, one or more volcanic vents may form at land surface. The conduit(s) supplying the vent(s) could pass through the repository, interacting with and entraining waste.	Included 10 CFR 63.311 (proposed)	Table 2.3.11-1
1.2.04.07.0A	Ashfall	Finely divided waste particles may be carried up a volcanic vent and deposited on the land surface from an ash cloud.	Included 10 CFR 63.311 (proposed)	Table 2.3.10-1 Table 2.3.11-1
1.2.04.07.0B	Ash Redistribution in Groundwater	Following deposition of contaminated ash on the surface, contaminants may leach out of the ash deposit and be transported through the subsurface to the compliance point.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.2.04.07.0C	Ash Redistribution Via Soil and Sediment Transport	Following deposition of contaminated ash on the surface, ash deposits may be redistributed on the surface via aeolian and fluvial processes.	Included 10 CFR 63.311 (proposed)	Table 2.3.11-1
1.2.05.00.0A	Metamorphism	If it occurs, metamorphism has the potential to affect the long-term performance of the repository. Metamorphism is defined as solid state changes to rock properties and geologic structures by means of recrystallization through the effects of heat and/or pressure.	Excluded low consequence	See Footnote
1.2.06.00.0A	Hydrothermal Activity	Naturally-occurring high-temperature groundwater may induce hydrothermal alteration of minerals in the rocks through which the high-temperature groundwater flows.	Excluded low consequence	See Footnote
1.2.07.01.0A	Erosion/ Denudation	Erosion and weathering are processes that can cause significant changes to the present-day topography through denudation and are thus capable of affecting both local and regional hydrology. Weathering refers to physical and chemical processes that alter and degrade rocks and soil at and near the land surface. Erosion involves the transport of surficial material away from the site by various mechanisms including glacial, fluvial, eolian (involving the wind), and chemical processes. Surficial materials, including weathering products, are also subject to gravity, and erosion can take place by mass wastage processes (e.g., landslides). The extent of denudation depends to a large extent on climate and the rate of local uplift.	Excluded low consequence	See Footnote
1.2.07.02.0A	Deposition	Deposition is a process that causes significant changes in the present-day topography and thus affects local and regional hydrology. Deposition of surficial materials can occur by a variety of means, including fluvial, aeolian, and lacustrine deposition and redistribution of soil through weathering and mass wasting processes.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.2.08.00.0A	Diagenesis	This FEP addresses natural processes that alter the mineralogy or other properties of rocks after the rocks have formed under temperature and pressure conditions normal to the upper few kilometers of the earth's crust. Diagenesis includes chemical, physical, and biological processes that take place in rocks after formation but before eventual metamorphism or weathering. This FEP refers to natural diagenetic processes only.	Excluded low consequence	See Footnote
1.2.09.00.0A	Salt Diapirism and Dissolution	This FEP addresses geologic processes that are primarily relevant to repositories located in salt deposits. Salt diapirism refers to the tendency of salt to flow under lithostatic loading when density and viscosity contrasts with surrounding strata are favorable. Such a process would modify the groundwater flow regime and affect radionuclide transport. Salt domes are the best-known example of salt diapirism. Dissolution can occur when any soluble mineral within the formation is removed by flowing water. Large-scale dissolution is a potentially important process in rocks that are composed predominantly of water-soluble evaporite minerals, such as salt.	Excluded low consequence	See Footnote
1.2.09.01.0A	Diapirism	Diapirism is the process by which plastic, low density rocks (most commonly evaporites) may flow under lithostatic loading when density and viscosity contrasts with the surrounding strata are favorable. Such a process would modify the groundwater flow regime and affect radionuclide transport.	Excluded low consequence	See Footnote
1.2.09.02.0A	Large-Scale Dissolution	Dissolution can occur when any soluble mineral is removed by flowing water. Large-scale dissolution is a potentially important process in rocks that are composed predominantly of water-soluble evaporite minerals, such as salt.	Excluded low consequence	See Footnote
1.2.10.01.0A	Hydrologic Response to Seismic Activity	Seismic activity, associated with fault movement, may create new or enhanced flow pathways and/or connections between stratigraphic units, or it may change the stress (and therefore fluid pressure) within the rock. These responses have the potential to significantly change the surface and groundwater flow directions, water level, water chemistry, and temperature.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.2.10.02.0A	Hydrologic Response to Igneous Activity	Igneous activity includes magmatic intrusions, which may alter groundwater flow pathways, and thermal effects that may heat up groundwater and rock. Igneous activity may change the groundwater flow directions, water level, water chemistry, and temperature. Eruptive and extrusive phases may change the topography, surface drainage patterns, and surface soil conditions. This may affect infiltration rates and locations.	Excluded low consequence	See Footnote
1.3.01.00.0A	Climate Change	Climate change may affect the long-term performance of the repository. This includes the effects of long-term change in global climate (e.g., glacial/interglacial cycles) and shorter-term change in regional and local climate. Climate is typically characterized by temporal variations in precipitation and temperature.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.1-1 Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2 Table 2.3.8-1 Table 2.3.9-1 Table 2.3.10-1
1.3.04.00.0A	Periglacial Effects	This FEP addresses the physical processes and associated landforms in cold but ice-sheet-free environments. Permafrost and seasonal freeze/thaw cycles are characteristic of periglacial environments. These effects could include erosion and deposition.	Excluded low consequence	See Footnote
1.3.05.00.0A	Glacial and Ice Sheet Effect	This FEP addresses the effects of glaciers and ice sheets occurring within the region of the repository, including direct geomorphologic effects and hydrologic effects. These effects include changes in topography (due to glaciation and melt water), changes in flow fields, and isostatic depression and rebound. These effects could include erosion and deposition.	Excluded low probability	See Footnote
1.3.07.01.0A	Water Table Decline	Climate change could produce decreased infiltration (e.g., an extended drought), leading to a decline in the water table in the saturated zone, which would affect the release and exposure pathways from the repository.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.3.07.02.0A	Water Table Rise Affects SZ	Climate change could produce increased infiltration, leading to a rise in the regional water table, possibly affecting radionuclide release from the repository by altering flow and transport pathways in the saturated zone. A regionally higher water table and change in saturated zone flow patterns might move discharge points closer to the repository.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1
1.3.07.02.0B	Water Table Rise Affects UZ	Climate change could produce increased infiltration, leading to a rise in the regional water table, possibly affecting radionuclide release from the repository by altering flow and transport pathways in the unsaturated zone. A regionally higher water table and change in unsaturated zone flow patterns might flood the repository.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.8-1
1.4.01.00.0A	Human Influences on Climate	Future human actions, either intentional or accidental, could influence global, regional, or local climate.	Excluded by Regulation	See Footnote
1.4.01.01.0A	Climate Modification Increases Recharge	Climate modification causes an increase in recharge in the Yucca Mountain region. Increased recharge might lead to increased flux through the repository, perched water, or water table rise.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.1-1 Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2 Table 2.3.8-1 Table 2.3.9-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.4.01.02.0A	Greenhouse Gas Effects	The greenhouse effect is the result of so-called “greenhouse gases” allowing incoming solar radiation to pass through the Earth's atmosphere, but preventing much of the outgoing infrared radiation from the surface and lower atmosphere from escaping into outer space. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halogenated fluorocarbons (HCFCs), ozone (O_3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs). Many of these gases are generated through various natural and physical processes, and have been responsible for maintaining habitable conditions on the planet. Human activities, such as burning fossil fuels, clearing forests (thereby increasing the oxidation of soil organic matter with the concurrent release of CO_2 as a decay product), most motorized transport and industrial processes have the potential to increase the levels of greenhouse gases, which could lead to changes in climate.	Excluded by Regulation	See Footnote
1.4.01.03.0A	Acid Rain	Acid rain refers to precipitation on a local to regional scale containing higher than normal amounts of nitric and sulfuric acids. This can result from man-made sources such as emissions produced from the burning of fossil fuels. Acid rain can detrimentally affect aquatic and terrestrial life by interfering with the growth, reproduction, and thus survival of affected organisms. It can influence the behavior and transport of contaminants in the biosphere, particularly by affecting surface water and soil chemistry and may also cause societal change due to contamination of water sources.	Excluded by Regulation	See Footnote
1.4.01.04.0A	Ozone Layer Failure	Human actions (i.e., the use of certain industrial chemicals) may lead to destruction or damage to the earth’s ozone layer. This may lead to significant changes to the climate, locally and globally, affecting properties of the geosphere such as groundwater flow patterns.	Excluded by Regulation	See Footnote
1.4.02.01.0A	Deliberate Human Intrusion	Humans could deliberately intrude into the repository, although without appropriate precautions, intruders could experience high radiation exposures. In addition, waste packages and other containment may be damaged during intrusion, thereby potentially increasing radionuclide release rates to the biosphere. Motivation for deliberate human intrusion includes mining for waste retrieval, site remediation/improvement activities, archaeological investigation, facility sabotage, and acts of war.	Excluded by Regulation	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.4.02.02.0A	Inadvertent Human Intrusion	Humans could accidentally intrude into the repository. Without appropriate precautions, intruders could experience high radiation exposures. Moreover, containment may be left damaged, which could increase radionuclide release rates to the biosphere. Inadvertent human intrusion might occur during scientific, mineral or geothermal exploration.	Included 10 CFR 63.321 (proposed)	Table 2.2-6
1.4.02.03.0A	Igneous Event Precedes Human Intrusion	An igneous event, such as a dike, could intersect the repository and significantly alter the material and structural properties of a drip shield and/or waste package. Because of the change in properties of these materials resulting from an igneous intrusion, an intruder, using groundwater exploration drilling techniques, may not be able to recognize that something other than naturally-occurring material has been encountered.	Excluded low probability	See Footnote
1.4.02.04.0A	Seismic Event Precedes Human Intrusion	A seismic event of sufficient magnitude to significantly alter the material and structural properties of a drip shield and/or waste package could occur in the vicinity of the repository. Because of the change in properties, an intruder, using groundwater exploration drilling techniques, may not be able to recognize that something other than naturally-occurring material has been encountered.	Excluded low consequence	See Footnote
1.4.03.00.0A	Unintrusive Site Investigation	This FEP concerns airborne, geophysical, or other surface-based investigations of a repository site area after its closure.	Excluded low consequence	See Footnote
1.4.04.00.0A	Drilling Activities (Human Intrusion)	This FEP addresses any type of drilling activity in the repository environment. These activities may be taken with or without awareness of the presence of the repository and with or without consent of the repository licensee. Drilling activities may be associated with natural resource exploration (water, oil and gas, minerals, geothermal energy), waste disposal (liquid), fluid storage (hydrocarbon, gas), or reopening existing boreholes.	Included 10 CFR 63.321 (proposed)	Table 2.2-6

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.4.04.01.0A	Effects of Drilling Intrusion	Drilling activities that intrude into the repository may create new release pathways to the biosphere and alter existing pathways. Possible effects of a drilling intrusion include interaction with waste packages, increased saturation in the repository leading to enhanced radionuclide transport to the saturated zone, changes to groundwater and EBS chemistry, and waste brought to the surface.	Included 10 CFR 63.321 (proposed)	Table 2.2-6
1.4.05.00.0A	Mining and Other Underground Activities (Human Intrusion)	Mining and other underground human activities (e.g., tunneling, underground construction, quarrying) could disrupt the disposal system and affect predicted repository performance.	Excluded by Regulation	See Footnote
1.4.06.01.0A	Altered Soil or Surface Water Chemistry	Human activities (e.g., those resulting in industrial pollution or those involving the use of agricultural chemicals) may produce local changes to the soil chemistry and, therefore, to the chemistry of water infiltrating Yucca Mountain. This could result in a contaminant plume of unspecified nature interacting with the repository and possibly with waste packages.	Excluded low consequence	See Footnote
1.4.07.01.0A	Water Management Activities	Water management is accomplished through a combination of dams, reservoirs, canals, pipelines, and collection and storage facilities. Water management activities could have a major influence on the behavior and transport of contaminants in the biosphere.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
1.4.07.02.0A	Wells	One or more wells drilled for human use (e.g., drinking water, bathing) or agricultural use (e.g., irrigation, animal watering) may intersect the contaminant plume.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1 Table 2.3.10-1
1.4.07.03.0A	Recycling of Accumulated Radionuclides from Soils to Groundwater	Radionuclides that have accumulated in soils (e.g., from deposition of contaminated irrigation water) may leach out of the soil and be recycled back into the groundwater as a result of recharge (either from natural or agriculturally induced infiltration). The recycled radionuclides may lead to enhanced radionuclide exposure at the receptor.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.4.08.00.0A	Social and Institutional Developments	Social and institutional developments could affect the long-term performance of the repository. The most likely is social and institutional development resulting in new activities, communities, or cities in the vicinity of Yucca Mountain.	Excluded by Regulation	See Footnote
1.4.09.00.0A	Technological Developments	Technological developments may affect the long-term performance of the repository. These include changes in the ability of humans to intrude the site, and changes that might affect contaminant exposure and its health implications.	Excluded by Regulation	See Footnote
1.4.11.00.0A	Explosions and Crashes (Human Activities)	Explosions or crashes resulting from future human activities may affect the long-term performance of the repository. Explosions may result from nuclear war, underground nuclear testing, or resource exploitation.	Excluded by Regulation	See Footnote
1.5.01.01.0A	Meteorite Impact	Meteorite impact close to the repository site might disturb or remove rock to such an extent that radionuclide transport to the surface is accelerated. Possible effects include alteration of flow patterns (by re-activation or formation of faults and fractures), changes in rock stress, cratering, and exhumation of waste.	Excluded low probability	See Footnote
1.5.01.02.0A	Extraterrestrial Events	Extraterrestrial events (e.g., supernova, solar flare, gamma-ray burster, and events associated with alien life forms) may affect long-term performance of the disposal system.	Excluded low consequence	See Footnote
1.5.02.00.0A	Species Evolution	Humans and other species living at or near the repository site may evolve in the future and their new behavior patterns and physiological characteristics may affect their likelihood of contaminant exposure and its consequent health implications.	Excluded by Regulation	See Footnote
1.5.03.01.0A	Changes in the Earth's Magnetic Field	Changes in the earth's magnetic field could affect the long-term performance of the repository.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
1.5.03.02.0A	Earth Tides	Small changes of the earth's gravitational field due to celestial movements (those of the sun and moon) cause earth tides and may, in turn, cause pressure variations in groundwater flow systems.	Excluded low consequence	See Footnote
2.1.01.01.0A	Waste Inventory	The waste inventory includes all potential sources of radio toxicity and chemical toxicity. It consists of the radionuclide inventory (typically in units of curies), by specific isotope, and the nonradionuclide inventory (typically in units of density or concentration), including chemical waste constituents. The radionuclide composition of the waste will vary due to initial enrichment, burn-up, the number of fuel assemblies per waste package, and the decay time subsequent to discharge of the fuel from the reactor.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.01.02.0A	Interactions Between Co-Located Waste	Colocation refers to the disposal of commercial SNF, DOE SNF, HLW, and possibly other wastes in close proximity within the repository. Colocation might affect thermal outputs, chemical interactions, or radionuclide mobilization.	Excluded low consequence	See Footnote
2.1.01.02.0B	Interactions Between Co-Disposed Waste	Codisposal refers to the disposal of different waste types within the same waste package. Codisposal might affect chemical interactions or radionuclide mobilization. At Yucca Mountain, the DOE SNF will be combined with HLW canisters within a waste package. This codisposal with HLW within a waste package is unique to the DOE SNF and does not apply to the commercial SNF or naval SNF placement within waste packages.The DOE SNF will be contained within canisters that will be placed within the waste packages. Some DOE SNF waste packages may contain only DOE SNF canisters, while others may contain both DOE SNF and HLW canisters.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.01.03.0A	Heterogeneity of Waste Inventory	Commercial SNF, DOE SNF, and HLW shipped to the repository may contain quantities of radionuclides that vary from waste package to waste package, fuel assembly to fuel assembly, and canister to canister. The composition of each of these waste forms may vary due to initial uranium enrichment, possible plutonium enrichment, and fuel burnup, among other factors. The physical state within the waste form may also vary. For example, damaged fuel pellets or extremely high-burnup fuels may have greater surface area exposed to any water penetrating a waste package than undamaged, low burnup spent fuel. Given these potential differences in isotopic composition and physical condition, the mass of radionuclides available for transport may vary significantly among waste packages.The different physical (structure, geometry), chemical, and radiological properties of the many forms of commercial SNF, DOE SNF, and HLW could result in differences in the corrosion and alteration rates based on waste-package composition. This could affect repository chemistry, breach times, dissolution rates, and availability of radionuclides for transport.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.01.04.0A	Repository-Scale Spatial Heterogeneity of Emplaced Waste	Waste placed in Yucca Mountain will have physical, chemical, and radiological properties that will vary spatially, resulting in variation in the mass of radionuclides available for transport from different parts of the repository.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.02.01.0A	DSNF Degradation (Alteration, Dissolution, and Radionuclide Release)	DOE SNF to be disposed in Yucca Mountain contains a variety of fuel types that include metallic uranium fuels; oxide and MOX fuels; Three Mile Island rubble; and heterogeneous fuels such as UAlx, U-ZrHx, and graphite fuels. In general, the composition and structure of these spent fuels are significantly different from commercial SNF, and the degradation, alteration, and dissolution may be different from the commercial SNF degradation. Processes to be considered in this FEP include alteration and dissolution of the various DSNF waste forms, phase separation, oxidation of spent fuels, selective leaching, and the effects of the disposal canister on DOE SNF degradation.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.02.02.0A	CSNF Degradation (Alteration, Dissolution, and Radionuclide Release)	Alteration of the original commercial SNF (under wet or dry conditions) and dissolution of the uranium-oxide matrix can influence the mobilization of radionuclides. The degradation of UO_2 could be affected by a number of variables, such as surface area, burn-up, temperature, overall solution electrochemical potential (Eh), pH, and especially solutions containing significant concentrations of calcium, sodium, carbonate, and silicate ions, as well as availability of organic complexing materials. In turn, these water properties are affected by the alteration of the cladding, fuel matrix and other waste package internals.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.02.03.0A	HLW Glass Degradation (Alteration, Dissolution, and Radionuclide Release)	Glass waste forms are thermal-dynamically unstable over long time periods, and will alter on contact with water. Radionuclides can be mobilized from the glass waste by a variety of processes, including degradation and alteration of the glass, phase separation, congruent dissolution, precipitation of silicates, coprecipitation of other minerals (including iron corrosion products), and selective leaching.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.02.04.0A	Alpha Recoil Enhances Dissolution	During decay of certain radionuclides, alpha particles may be emitted with sufficiently high energies that the daughter nuclide recoils appreciably to conserve system momentum. A potential result of recoil is that certain radionuclides, such as ^{234}U, exhibit substantially greater dissolution rates (with the same solubility limits) and can be transported preferentially.	Excluded low consequence	See Footnote
2.1.02.05.0A	HLW Glass Cracking	Cracking of the HLW glass on cooling and during handling means that the surface area of the glass is greater than the surface area of a monolithic block. The increase in the surface area could affect the rate of glass alteration and radionuclide dissolution.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.02.06.0A	HLW Glass Recrystallization	HLW glass recrystallization could occur and would lead to a less corrosion-resistant waste form. Recrystallization is a slow process and typically occurs only if a high glass temperature is maintained over a prolonged period.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.02.07.0A	Radionuclide Release from Gap and Grain Boundaries	While in the reactor at high temperatures, radionuclides such as iodine and cesium may migrate and preferentially accumulate in cracks in the fuel matrix, grain boundaries of the UO_2, and in the gap between the fuel and cladding. After the waste package fails and the cladding perforates, the release rate of this fraction of the radionuclides could be rapid.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.02.08.0A	Pyrophoricity from DSNF	DOE SNF can contain pyrophoric material. Pyrophoric material could ignite and produce an adverse effect on repository performance. Pyrophoric events could affect the thermal behavior of the system and could contribute to degradation of the waste package, waste form, and cladding.	Excluded low consequence	See Footnote
2.1.02.09.0A	Chemical Effects of Void Space in Waste Package	If waste packages and/or DOE SNF canisters are not completely filled, then the unfilled inert gas or air-filled volume could influence water-chemistry calculations.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.02.10.0A	Organic/Cellulosic Materials in Waste	Degradation of cellulose in the waste could affect the long-term performance of the disposal system.	Excluded low consequence	See Footnote
2.1.02.11.0A	Degradation of Cladding from Waterlogged Rods	Failed fuel rods (attributed to breaches caused by manufacturing defects and reactor operations) comprise a small fraction of the fuel rods that are currently being stored in commercial reactor spent fuel pools. Failed fuel contains water in the fuel rod void space that may promote degradation of the spent fuel cladding. Such fuel is referred to as “waterlogged.” The moisture remaining in a “dried” fuel rod is used to determine the extent of degradation of spent fuel cladding.	Excluded low consequence	See Footnote
2.1.02.12.0A	Degradation of Cladding Prior to Disposal	Certain aspects of cladding degradation may occur before the spent fuel arrives at Yucca Mountain. Possible mechanisms include rod cladding degradation during reactor operation, degradation during wet spent fuel pool storage, degradation during dry storage, and rod degradation during transportation (e.g., from creep and from vibration and impact) and fuel handling.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.02.13.0A	General Corrosion of Cladding	General corrosion of cladding could expose large areas of fuel and produce hydrides.	Excluded low consequence	See Footnote
2.1.02.14.0A	Microbially Influenced Corrosion (MIC) of Cladding	Microbially influenced corrosion of cladding is a potential localized corrosion mechanism where microbes produce a local acidic environment that could produce multiple penetrations through the fuel cladding.	Excluded low consequence	See Footnote
2.1.02.15.0A	Localized (Radiolysis Enhanced) Corrosion of Cladding	Radiolysis in a nitrogen/oxygen gas mixture with the presence of water film results in the formation of nitric acid (HNO_3). Hydrogen peroxide (H_2O_2) is formed in the water from radiolysis. These chemicals can enhance corrosion of the fuel cladding.	Excluded low consequence	See Footnote
2.1.02.16.0A	Localized (Pitting) Corrosion of Cladding	Localized corrosion in pits could produce penetrations of cladding.	Excluded low consequence	See Footnote
2.1.02.17.0A	Localized (Crevice) Corrosion of Cladding	Localized corrosion in crevices could produce penetrations of cladding.	Excluded low consequence	See Footnote
2.1.02.18.0A	Enhanced Corrosion of Cladding from Dissolved Silica	High dissolved silica content of waters may enhance corrosion of cladding.	Excluded low consequence	See Footnote
2.1.02.19.0A	Creep Rupture of Cladding	At high temperatures (>400°C) for sufficiently long time intervals, creep rupture of Zircaloy cladding on spent fuel can occur and produce small perforations in the cladding to relieve stress. After the waste package fails, the fuel can react with water and radionuclides can escape over time from the fuel rod.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.02.20.0A	Internal Pressurization of Cladding	Increased pressure within the fuel rod due to the production of helium gas could contribute to cladding failure.	Excluded low consequence	See Footnote
2.1.02.21.0A	Stress Corrosion Cracking (SCC) of Cladding	Stress corrosion cracking mechanisms can contribute to cladding failure. These mechanisms can operate both from the inside out from the action of fission products, or from the outside in from the actions of salts or other chemicals within the waste package.	Excluded low consequence	See Footnote
2.1.02.22.0A	Hydride Cracking of Cladding	Cladding contains hydrogen after reactor operation. The cladding might pick up more hydrogen from cladding general corrosion (wet oxidation) after the waste package is breached. The hydrogen can exist both as zirconium hydride precipitates and as hydrogen in solid solution with zirconium. Hydrides might also form from UO_2 oxidation after waste package and cladding perforation. In addition, hydrides may dissolve in warmer areas of the cladding and migrate to cooler areas. Hydrogen can also move from places of low stress to places of high stress, causing hydride reorientation or delayed hydride cracking. The buildup of hydrides can cause existing cracks to propagate by delayed hydride cracking or hydride embrittlement.	Excluded low consequence	See Footnote
2.1.02.23.0A	Cladding Unzipping	In either dry or wet oxidizing conditions and with perforated fuel cladding, the UO_2 fuel can oxidize. The volume increase of the fuel as it oxidizes can create stresses in the cladding that may cause gross rupture of the fuel cladding (unzipping).	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.02.24.0A	Mechanical Impact on Cladding	Mechanical failure of cladding may result from external stresses, such as rockfall or impact from waste package internals. Seismic-induced impacts are addressed in several separate FEPs.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.02.25.0A	DSNF Cladding	DOE SNF to be disposed in Yucca Mountain contains a variety of fuel types that may not be similar to commercial SNF. Some of the fuel types may have initial cladding-degradation characteristics that are different from those for commercial SNF. Therefore, the effectiveness of DOE SNF cladding as a barrier to radionuclide mobilization might be different from commercial SNF. This FEP addresses all types of DOE SNF cladding except naval SNF cladding.	Excluded low consequence	See Footnote
2.1.02.25.0B	Naval SNF Cladding	DOE SNF to be disposed of in Yucca Mountain has a variety of fuel types that may not be similar to the commercial SNF to be disposed. Some of the fuel types may have initial cladding-degradation characteristics that are different from those for the commercial SNF. Therefore, the effectiveness of DOE SNF cladding as a barrier to radionuclide mobilization might be different from commercial SNF. This FEP addresses naval SNF structure only.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1 See Naval Nuclear Propulsion Program Technical Support Document, Section 2.3.7
2.1.02.26.0A	Diffusion-Controlled Cavity Growth in Cladding	Diffusion-controlled cavity growth is a possible creep rupture mechanism that could occur under the temperature and pressure conditions that prevail during dry storage of spent fuel. It might also occur during disposal.	Excluded low consequence	See Footnote
2.1.02.27.0A	Localized (Fluoride Enhanced) Corrosion of Cladding	Fluoride is present in Yucca Mountain groundwater, and zirconium has been observed to corrode in environments containing fluoride. Therefore, fluoride corrosion of cladding may occur in waste packages.	Excluded low consequence	See Footnote
2.1.02.28.0A	Grouping of DSNF Waste Types into Categories	Several hundred distinct types of DOE SNF may potentially be stored in the repository. These represent many more types than can viably be examined for their individual effect on the repository. A limited number of representative or bounding degradation models must be selected and/or abstracted.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.02.29.0A	Flammable Gas Generation from DSNF	DOE SNF to be disposed in Yucca Mountain will contain a small percentage of carbide fuel. When carbide is exposed to water, flammable gases such as methane, ethane, ethylene, and acetylene (the latter two are referred to as ethene and ethyne, respectively, by the International Union of Pure and Applied Chemistry) are generated. If these gases ignite, localized increases in temperature can occur, which might affect fuel degradation. The area around the ignition point may be mechanically and/or thermally perturbed, which could affect waste package or host-rock properties in the adjacent area of the EBS.	Excluded low consequence	See Footnote
2.1.03.01.0A	General Corrosion of Waste Packages	General corrosion may contribute to waste package failure.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.6-2
2.1.03.01.0B	General Corrosion of Drip Shields	General corrosion may contribute to drip shield failure.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.6-2
2.1.03.02.0A	Stress Corrosion Cracking (SCC) of Waste Packages	Waste packages may become wet at specific locations that are stressed leading to stress corrosion cracking. The possibility of stress corrosion cracking under dry conditions or due to thermal stresses are also addressed as part of this FEP.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.6-2
2.1.03.02.0B	Stress Corrosion Cracking (SCC) of Drip Shields	Drip shields may become wet at specific locations that are stressed leading to stress corrosion cracking. The possibility of stress corrosion cracking under dry conditions or due to thermal stresses are also addressed as part of this FEP.	Excluded low consequence	See Footnote
2.1.03.03.0A	Localized Corrosion of Waste Packages	Localized corrosion (pitting or crevice corrosion) could enhance degradation of the waste packages.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.6-2

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.03.03.0B	Localized Corrosion of Drip Shields	Localized corrosion (pitting or crevice corrosion) could enhance degradation of the drip shields.	Excluded low probability	See Footnote
2.1.03.04.0A	Hydride Cracking of Waste Packages	The uptake of hydrogen and the formation of metal hydrides may mechanically weaken the waste packages and promote degradation.	Excluded low probability	See Footnote
2.1.03.04.0B	Hydride Cracking of Drip Shields	The uptake of hydrogen and the formation of metal hydrides may mechanically weaken the drip shields and promote degradation.	Excluded low probability	See Footnote
2.1.03.05.0A	Microbially Influenced Corrosion (MIC) of Waste Packages	Microbial activity may either directly (e.g., direct enhancement of the dissolution rate) or indirectly (e.g., through the formation of chemical species which in turn support increased metal oxidation) enhance the corrosion rate of the waste package, leading to an acceleration of the corrosion rate beyond the levels anticipated based upon the bulk environment to which it is exposed.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.6-2
2.1.03.05.0B	Microbially Influenced Corrosion (MIC) of Drip Shields	Microbial activity may either directly (e.g., direct enhancement of the dissolution rate) or indirectly (e.g., through the formation of chemical species which in turn support increased metal oxidation) enhance the dissolution rate of the drip shield, leading to an acceleration of the corrosion rate beyond the levels anticipated based upon the bulk environment to which it is exposed.	Excluded low consequence	See Footnote
2.1.03.06.0A	Internal Corrosion of Waste Packages Prior to Breach	Aggressive chemical conditions within the waste package could contribute to corrosion from the inside out. Effects of different waste forms, including commercial SNF and DOE SNF, are considered in this FEP.	Excluded low consequence	See Footnote
2.1.03.07.0A	Mechanical Impact on Waste Package	Mechanical impact (dynamic loading) on the waste package may be caused by internal and external forces such as internal gas pressure, forces caused by swelling of corrosion products, rockfall, and possible waste package or drip shield movement. Seismic-induced impacts are addressed in included FEP 1.2.03.02.0A, Seismic ground motion damages EBS components.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.03.07.0B	Mechanical Impact on Drip Shield	Mechanical impact (dynamic loading) on the drip shield may be caused by forces such as rockfall and possible waste package or drip shield movement. Seismic-induced impacts are addressed in separate FEPs.	Excluded low consequence	See Footnote
2.1.03.08.0A	Early Failure of Waste Packages	Waste packages may fail prematurely because of manufacturing defects, improper sealing, or other factors related to quality control during manufacture and emplacement.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.6-2
2.1.03.08.0B	Early Failure of Drip Shields	Drip shields may fail prematurely because of manufacturing defects, improper sealing, or other factors related to quality control during manufacture and emplacement.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.6-2
2.1.03.09.0A	Copper Corrosion in EBS	Chemical reactions involving copper corrosion have been identified as being of potential interest for repository programs considering the use of copper containers.	Excluded low consequence	See Footnote
2.1.03.10.0A	Advection of Liquids and Solids Through Cracks in the Waste Package	The presence of one or more cracks or other small openings of sufficient size in a waste package may provide a pathway for the advective flow of water (e.g., thin films or droplets) or solid material into the waste package. The resulting presence of sufficient water or solid material in the waste package may affect in-package chemistry and/or criticality. Partial or full plugging of the waste package cracks by chemical or physical reactions after their formation (i.e., healing) could also affect water flow and radionuclide transport through the waste package. Passivation by corrosion products is a potential mechanism for waste package healing.	Excluded low consequence	See Footnote
2.1.03.10.0B	Advection of Liquids and Solids Through Cracks in the Drip Shield	The presence of one or more cracks or other small openings of sufficient size in a drip shield may provide a pathway for the advective flow of water (e.g., thin films or droplets) or solid material through the drip shield. The resulting flux may affect drip shield performance and/or subsequent dripping onto the waste packages. Partial or full plugging of the drip shield cracks by chemical or physical reactions after their formation (i.e., healing) could also affect water flow through the drip shield.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.03.11.0A	Physical form of Waste Package and Drip Shield	The specific forms of the various drip shields, waste packages, and internal waste containers that are proposed for the Yucca Mountain repository can affect long-term performance. Waste package form may affect container strength through the shape and dimensions of the waste package and affect heat dissipation through waste package volume and surface area. Waste package and drip shield materials may affect physical and chemical behavior of the disposal area environment. Waste package and drip shield integrity will affect the releases of radionuclides from the disposal system. Waste packages may have both local effects and repository-scale effects. All types of waste packages and containers, including commercial SNF, DOE SNF, and DOE HLW, should be considered.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-2 Table 2.3.5-3 Table 2.3.6-2 Table 2.3.7-1
2.1.04.01.0A	Flow in the Backfill	Preferential pathways for flow and diffusion may exist within the backfill and may affect long-term performance of the waste packages. Backfill may not preclude hydrologic, chemical, and thermal interactions between waste packages within a drift.	Excluded low consequence	See Footnote
2.1.04.02.0A	Chemical Properties and Evolution of Backfill	The chemical properties of the backfill may affect groundwater flow, waste package and drip shield durability, and radionuclide transport in the waste disposal region. Properties of the backfill may change through time, due to processes such as alteration of minerals.	Excluded low consequence	See Footnote
2.1.04.03.0A	Erosion or Dissolution of Backfill	Solid material in backfill may be carried away by flowing groundwater, either by erosion of particulate matter or by dissolution.	Excluded low consequence	See Footnote
2.1.04.04.0A	Thermal-Mechanical Effects of Backfill	Backfill may alter the mechanical evolution of the drift environment by providing resistance to rockfall and drift collapse, by changing the thermal properties of the drift, or by other means. Impacts of the evolution of the properties of the backfill itself should be considered.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.04.05.0A	Thermal-Mechanical Properties and Evolution of Backfill	The physical properties of the backfill may affect groundwater flow, waste package and drip shield durability, and radionuclide transport in the waste disposal region. Properties of the backfill may change through time, due to processes such as silica cementation, thermal effects, and physical compaction.	Excluded low consequence	See Footnote
2.1.04.09.0A	Radionuclide Transport in Backfill	Radionuclide transport in the drift environment may be affected by the presence of backfill. Transport (i.e., advective and diffusive effects and sorption processes) of both dissolved and colloidal species should be considered.	Excluded low consequence	See Footnote
2.1.05.01.0A	Flow Through Seals (Access Ramps and Ventilation Shafts)	Long-term fluid flow through the shaft seal system, and uncertainty about long-term properties of the shaft seal system, may influence cumulative radionuclide releases from the disposal system.	Excluded low consequence	See Footnote
2.1.05.02.0A	Radionuclide Transport Through Seals	Groundwater flow through seals in the access ramps, ventilation shafts, and exploratory boreholes could affect long-term performance of the disposal system. Radionuclide transport through seals should be considered.	Excluded low consequence	See Footnote
2.1.05.03.0A	Degradation of Seals	Degradation of seals in the access ramps, ventilation shafts, and exploratory boreholes could modify flow and transport properties. Physical properties of the seals emplaced in the access ramps, ventilation shafts, and exploratory boreholes may affect the long-term performance of the disposal system. These properties include the location of the seals (and the openings they seal), and the physical and chemical characteristics of the sealing materials. Possible mechanisms for seal degradation include: chemical alteration from water interactions, wetting associated with condensation, and thermally-induced stress-strain changes.	Excluded low consequence	See Footnote
2.1.06.01.0A	Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS	Degradation of ground support material (e.g., cement, rock bolts, wire mesh) used for any purpose in the disposal region may affect long-term performance through both chemical and physical processes. Degradation may occur by physical, chemical, and microbial processes.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.06.02.0A	Mechanical Effects of Rock Reinforcement Materials in EBS	Degradation of rock bolts, wire mesh, and other materials used in ground control may affect the long-term performance of the repository.	Excluded low consequence	See Footnote
2.1.06.04.0A	Flow Through Rock Reinforcement Materials in EBS	Groundwater flow may occur through the ground support materials (e.g., wire mesh, rock bolts, grout) and liner (if present).	Excluded low consequence	See Footnote
2.1.06.05.0A	Mechanical Degradation of Emplacement Pallet	Degradation of the materials used in the pallet supporting the waste package may occur by physical processes, and may affect the long-term performance of the repository. Degradation may be fast (e.g., from dynamic loading) or slow (e.g., from static loading).	Excluded low consequence	See Footnote
2.1.06.05.0B	Mechanical Degradation of Invert	Degradation of the materials used in the invert may occur by physical processes, and may affect the long-term performance of the repository. Degradation may be fast (e.g., from dynamic loading) or slow (e.g., from static loading).	Excluded low consequence	See Footnote
2.1.06.05.0C	Chemical Degradation of Emplacement Pallet	Degradation of the materials used in the pallet supporting the waste package may occur by chemical or microbial processes, and may affect the long-term performance of the repository.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.4-1
2.1.06.05.0D	Chemical Degradation of Invert	Degradation of the materials used in the invert may occur by chemical or microbial processes, and may affect the long-term performance of the repository.	Excluded low consequence	See Footnote
2.1.06.06.0A	Effects of Drip Shield on Flow	The drip shield will affect the amount of water reaching the waste package. Effects of the drip shield on the disposal region environment (for example, changes in relative humidity and temperature below the shield) should be considered for both intact and degraded conditions.	Included 10 CFR 63.311 10 CFR 63.331	Table 2.3.7-1 Table 2.3.5-2

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.06.06.0B	Oxygen Embrittlement of Drip Shields	A potential failure mechanism for drip shields is oxygen embrittlement, resulting from the diffusion of interstitial oxygen in the titanium at high temperatures.	Excluded low probability	See Footnote
2.1.06.07.0A	Chemical Effects at EBS Component Interfaces	Chemical effects that occur at the interfaces between materials in the drift may affect the performance of the system.	Excluded low consequence	See Footnote
2.1.06.07.0B	Mechanical Effects at EBS Component Interfaces	Physical effects of steady-state contact (static loading) that occur at the interfaces between materials in the drift may affect the performance of the system.	Excluded low consequence	See Footnote
2.1.07.01.0A	Rockfall	Rockfall may occur with blocks that are large enough to mechanically tear or rupture drip shields and/or waste packages. Seismic-induced rockfall is addressed in separate FEPs.	Excluded low consequence	See Footnote
2.1.07.02.0A	Drift Collapse	Partial or complete collapse of the drifts, as opposed to discrete rockfall, could occur as a result of thermal effects, stresses related to excavation, or other mechanisms. Drift collapse could affect the stability of the engineered barriers and waste packages and/or result in static loading from rock overburden. Rockfalls of small blocks may produce rubble throughout part or all of the drifts. Seismic-induced drift collapse is addressed in a separate FEP.	Excluded low consequence	See Footnote
2.1.07.04.0A	Hydrostatic Pressure on Waste Package	Waste packages emplaced in the saturated zone will be subjected to hydrostatic pressure in addition to stresses associated with the evolution of the waste and EBS.	Excluded low probability	See Footnote
2.1.07.04.0B	Hydrostatic Pressure on Drip Shield	Drip shields emplaced in the saturated zone will be subjected to hydrostatic pressure in addition to stresses associated with the evolution of the waste and EBS.	Excluded low probability	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.07.05.0A	Creep of Metallic Materials in the Waste Package	Metals used in the waste package may deform by creep processes in response to deviatoric stress or internal void space.	Excluded low consequence	See Footnote
2.1.07.05.0B	Creep of Metallic Materials in the Drip Shield	Metals used in the drip shield may deform by creep processes in response to deviatoric stress.	Excluded low consequence	See Footnote
2.1.07.06.0A	Floor Buckling	Buckling, or heave, of the drift floor may occur in response to changing stress. Floor buckling may affect the performance of EBS components such as the drip shield, the invert, and the pallet. Effects may include movement of EBS components and changes in the topography of the surface of the drift floor and invert that may affect water flow.	Excluded low consequence	See Footnote
2.1.08.01.0A	Water Influx at the Repository	An increase in the unsaturated water flux at the repository may affect thermal, hydrologic, chemical, and mechanical behavior of the system. Increases in flux could result from climate change, but the cause of the increase is not an essential part of the FEP.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-2 Table 2.3.8-1
2.1.08.01.0B	Effects of Rapid Influx Into the Repository	Extremely rapid influx could reduce temperatures below the boiling point during part or all of the thermal period. Increases in flux could result from climate change, but the cause of the increase is not an essential part of the FEP.	Excluded low consequence	See Footnote
2.1.08.02.0A	Enhanced Influx at the Repository	An opening in unsaturated rock may alter the hydraulic potential, affecting local saturation around the opening and redirecting flow. Some of the flow may be directed to the opening where it is available to seep into the opening.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.3-1
2.1.08.03.0A	Repository Dry-Out Due to Waste Heat	Repository heat evaporates water from the unsaturated zone rocks near the drifts, as the temperature exceeds the vaporization temperature. This zone of reduced water content (reduced saturation) could migrate outward during the heating phase and then migrate back to the waste package as heat diffuses throughout the mountain and the radioactive heat sources decay. This FEP addresses the effects of dryout within the repository drifts.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.5-2

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.08.04.0A	Condensation Forms on Roofs of Drifts (Drift-Scale Cold Traps)	Emplacement of waste in drifts creates thermal gradients within the repository. Such thermal gradients can lead to drift-scale cold traps characterized by latent heat transfer from warmer to cooler locations. This mechanism can result in condensation forming on the roof or other parts of the drifts, leading to enhanced dripping on the drip shields, waste packages, or exposed waste material.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.5-2
2.1.08.04.0B	Condensation Forms at Repository Edges (Repository-Scale Cold Traps)	Emplacement of waste in drifts creates thermal gradients within the repository. Such thermal gradients can lead to repository-scale cold traps characterized by latent heat transfer from warmer to cooler locations. This mechanism can result in condensation forming at repository edges or elsewhere in the EBS, leading to enhanced dripping on the drip shields, waste packages, or exposed waste material.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.5-2
2.1.08.05.0A	Flow Through Invert	The invert, a porous material consisting of crushed tuff, separates the waste package from the bottom of the drift. Flow and transport through and around the invert can influence radionuclide release to the unsaturated zone.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.5-2 Table 2.3.7-1
2.1.08.06.0A	Capillary Effects (Wicking) in EBS	Capillary rise, or wicking, is a potential mechanism for water to move through the waste and EBS.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.5-2 Table 2.3.5-3 Table 2.3.7-1
2.1.08.07.0A	Unsaturated Flow in the EBS	Unsaturated flow may occur along preferential pathways in the waste and EBS. Physical and chemical properties of the EBS and waste form, in both intact and degraded states, should be considered in evaluating pathways.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-2 Table 2.3.7-1
2.1.08.09.0A	Saturated Flow in the EBS	Saturated flow and radionuclide transport may occur along preferential pathways in the waste and EBS. Physical and chemical properties of the EBS and waste form, in both intact and degraded states, should be considered in evaluating pathways.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.08.11.0A	Repository Resaturation Due to Waste Cooling	Following the peak thermal period, water in the condensation cap may flow downward, resaturating the geosphere dryout zone and flowing into the drifts. This may lead to an increase in water content and/or resaturation in the repository.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.5-2 Table 2.3.5-3
2.1.08.12.0A	Induced Hydrologic Changes in Invert	Drainage in the drifts may be altered by plugging of fractures or floor buckling. Possible effects include wetting or ponding in the invert until the water level reaches the fractures in the wall or until there is sufficient hydraulic head to clear the fractures. Wetting or ponding could provide a continuing source of water vapor for interaction with the drip shields, waste packages, and their supports.	Excluded low consequence	See Footnote
2.1.08.14.0A	Condensation on Underside of Drip Shield	Condensation of water on the underside of the drip shield may affect the waste package hydrologic and chemical environment.	Excluded low consequence	See Footnote
2.1.08.15.0A	Consolidation of EBS Components	Physical and chemical degradation of the drip shield, invert, waste form, and waste package may cause collapse and settlement within the repository. This consolidation may affect the development of the chemical environment and, therefore, the radionuclide transport out of the EBS.	Excluded low consequence	See Footnote
2.1.09.01.0A	Chemical Characteristics of Water in Drifts	When flow in the drifts is re-established following the peak thermal period, water may have chemical characteristics influenced by the near-field host rock and EBS. Specifically, the water chemistry (pH and dissolved species in the groundwater) may be affected by interactions with cementitious materials or steel used in the disposal region. These point source contaminated waters may coalesce to form a larger volume of contaminated water. This altered groundwater is referred to as the carrier plume because dissolution and transport will occur in this altered chemical environment as contaminants move through the EBS, and down into the unsaturated zone. (Note: There is no defining limit as to what volume of contaminated water constitutes a plume.)	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-3 Table 2.3.7-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.09.01.0B	Chemical Characteristics of Water in Waste Package	Chemical characteristics of the water in the waste packages (pH and dissolved species) may be affected by interactions with steel and other materials used in the waste packages or waste forms, as well as by the inflowing water from the drifts and near-field host rock. The in-package chemistry, in turn may influence dissolution and transport as contaminants move through the waste, EBS, and down into the unsaturated zone.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.02.0A	Chemical Interaction with Corrosion Products	Corrosion products produced during degradation of the waste form, metallic portions of the waste package, and metals in the drift (i.e., rock bolts, steel in the invert, gantry rails) may affect the mobilization and transport of radionuclides. Corrosion products may facilitate sorption/desorption and co-precipitation/dissolution processes. Corrosion products may form a “rind” around the fuel that could (1) restrict the availability of water for dissolution of radionuclides or (2) inhibit advective or diffusive transport of water and radionuclides from the waste form to the EBS. Corrosion products also have the potential to retard the transport of radionuclides to the EBS. Finally, corrosion products may alter the local chemistry, possibly enhancing dissolution rates for specific waste forms, or altering radionuclide solubility.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.03.0A	Volume Increase of Corrosion Products Impacts Cladding	Corrosion products have a higher molar volume than the intact, uncorroded material. Increases in volume during waste form and cladding corrosion could change the stress state in the material being corroded and lead to cladding unzipping.	Excluded low consequence	See Footnote
2.1.09.03.0B	Volume Increase of Corrosion Products Impacts Waste Package	Corrosion products have a higher molar volume than the intact, uncorroded material. Increases in volume during waste form, cladding, and waste package corrosion could change the stress state in the material being corroded and lead to waste package damage.	Excluded low consequence	See Footnote
2.1.09.03.0C	Volume Increase of Corrosion Products Impacts Other EBS Components	Corrosion products have a higher molar volume than the intact, uncorroded material. This FEP addresses volume increase in all EBS components other than waste package, waste form, and cladding. Increases in volume during corrosion of steel in the invert may change the stress state or structural integrity of the invert.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.09.04.0A	Radionuclide Solubility, Solubility Limits, and Speciation in the Waste Form and EBS	Degradation of the waste form will mobilize radionuclides in the aqueous phase. Factors to be considered in this FEP include the initial radionuclide inventory, justification of the limited inventory included in evaluations of aqueous concentrations, and the solubility limits for those radionuclides.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.05.0A	Sorption of Dissolved Radionuclides in EBS	Sorption of dissolved radionuclides within the waste package may affect the aqueous concentrations of radionuclides released to the EBS.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.06.0A	Reduction-Oxidation Potential in Waste Package	The redox potential in the waste package influences the oxidation of waste form materials and the in-package solubility of radionuclide species. Local variations in the in-package redox potential can occur.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.06.0B	Reduction-Oxidation Potential in Drifts	The redox potential in the EBS influences the oxidation of the in-drift materials and the in-drift solubility of radionuclide species. Local variations in the in-drift redox potential can occur.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-3
2.1.09.07.0A	Reaction Kinetics in Waste Package	Chemical reactions, such as radionuclide dissolution/ precipitation reactions and reactions controlling the reduction-oxidation state, may not be at equilibrium within the waste package.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.07.0B	Reaction Kinetics in Drifts	Chemical reactions, such as radionuclide dissolution/precipitation reactions and reactions controlling the reduction-oxidation state, may not be at equilibrium in the drifts.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-3

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.09.08.0A	Diffusion of Dissolved Radionuclides in EBS	Radionuclide transport of dissolved radionuclides by diffusion, in response to chemical gradients, may occur within the EBS. Physical and chemical properties of the EBS and waste form, in both intact and degraded states, should be considered in evaluating diffusive transport.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.08.0B	Advection of Dissolved Radionuclides in EBS	Radionuclide transport of dissolved radionuclides by advection with the flowing groundwater may occur within the EBS. Physical and chemical properties of the EBS and waste form, in both intact and degraded states, should be considered in evaluating advective transport.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.09.0A	Electrochemical Effects in EBS	Electrochemical effects may establish an electric potential within the drift or between materials in the drift and more distant metallic materials. Migration of ions within such an electric field could affect corrosion of metals in the EBS and waste, and could also have a direct effect on the transport of radionuclides as charged ions.	Excluded low consequence	See Footnote
2.1.09.10.0A	Secondary Phase Effects on Dissolved Radionuclide Concentrations	Inclusion of radionuclides in secondary uranium mineral phases, such as neptunium in schoepite and uranium silicates, could affect radionuclide concentrations in water in contact with the waste form. During radionuclide alteration, the radionuclides could be chemically bound to immobile compounds and result in a reduction of available radionuclides for mobilization.	Excluded low consequence	See Footnote
2.1.09.11.0A	Chemical Effects of Waste-Rock Contact	Waste (commercial SNF, DOE SNF, and HLW) and rock may be placed in direct contact by mechanical failure of the drip shields and/or waste packages. Chemical effects on the waste (e.g., dissolution) may be enhanced or altered in a system where waste, rock minerals, and water are all in physical contact with one another, relative to a system where only waste and water are in physical contact.	Excluded low consequence	See Footnote
2.1.09.12.0A	Rind (Chemically Altered Zone) Forms in the Near-Field	Thermal-chemical processes involving precipitation, condensation, and redissolution could alter the properties of the adjacent rock. These alterations may form a rind, or altered zone, in the rock, with hydrologic, thermal, and mineralogical properties different from the initial conditions.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.09.13.0A	Complexation in EBS	The presence of organic complexants in water in the EBS could augment radionuclide transport by providing a transport mechanism in addition to simple diffusion and advection of dissolved material. Organic complexants may include materials found in natural groundwater such as humates and fulvates, or materials introduced with the waste or engineered materials.	Excluded low consequence	See Footnote
2.1.09.15.0A	Formation of True (Intrinsic) Colloids in EBS	True colloids are colloidal-sized assemblages (between approximately 1 nm and 1 µm in diameter) consisting of hydrolyzed and polymerized radionuclides. They may form in the waste package and EBS during waste form degradation and radionuclide transport. True colloids are also called primary colloids, real colloids, Type I colloids, Eigenkolloide, and intrinsic colloids (or actinide intrinsic colloids, for those including actinide elements).	Excluded low consequence	See Footnote
2.1.09.16.0A	Formation of Pseudo-Colloids (Natural) in EBS	Pseudo-colloids are colloidal-sized assemblages (between approximately 1 nm and 1 µm in diameter) of nonradioactive material that have radionuclides bound or sorbed to them. Natural pseudo-colloids include microbial colloids, mineral fragments (i.e., clay, silica, iron oxyhydroxides), and humic and fulvic acids. This FEP addresses radionuclide-bearing pseudo-colloids formed from host-rock materials and all interactions of the waste and EBS with the host rock environment except corrosion.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.17.0A	Formation of Pseudo-Colloids (Corrosion Product) in EBS	Pseudo-colloids are colloidal-sized assemblages (between approximately 1 nm and 1 µm in diameter) of nonradioactive material that have radionuclides bound or sorbed to them. Corrosion product pseudo-colloids include iron oxyhydroxides from corrosion and degradation of the metals in the EBS and silica from degradation of cementitious materials.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.18.0A	Formation of Microbial Colloids in EBS	This FEP addresses the formation and transport of microbial colloids in the waste and EBS.	Excluded low consequence	See Footnote
2.1.09.19.0A	Sorption of Colloids in EBS	Interactions between radionuclide-bearing colloids and the waste and EBS may result in retardation of the colloids during transport by sorption mechanisms.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.09.19.0B	Advection of Colloids in EBS	Transport of radionuclide-bearing colloids in the waste and EBS may occur by advection.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.20.0A	Filtration of Colloids in EBS	Filtration processes may affect transport of radionuclide-bearing colloids in the waste and EBS. Filtration includes physical and electrostatic processes in pores and fractures of natural and anthropogenic materials, such as concrete and the joints between invert segments.	Excluded low consequence	See Footnote
2.1.09.21.0A	Transport of Particles Larger than Colloids in EBS	Groundwater flow through the waste could remove radionuclide-bearing particles by a rinse mechanism. Particles of radionuclide-bearing material larger than colloids could be entrained in suspension and then be transported in water flowing through the waste and EBS.	Excluded low consequence	See Footnote
2.1.09.21.0B	Transport of Particles Larger than Colloids in the SZ	Particles of radionuclide-bearing material larger than colloids could be entrained in suspension and then be transported in water flowing through the saturated zone.	Excluded low consequence	See Footnote
2.1.09.21.0C	Transport of Particles Larger than Colloids in the UZ	Particles of radionuclide-bearing material larger than colloids could be entrained in suspension and then be transported in water flowing through the unsaturated zone.	Excluded low consequence	See Footnote
2.1.09.22.0A	Sorption of Colloids at Air-Water Interface	Colloids may be sorbed irreversibly at the air-water interface under partially saturated conditions.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.09.23.0A	Stability of Colloids in EBS	For radionuclide-bearing colloids to affect repository performance, they must remain suspended in the groundwater (i.e., be stable) for time scales that are long relative to the time required for groundwater travel. Further, they must carry significant concentrations of radionuclides. The stability of smectite colloids (applicable for natural groundwater colloids and waste form colloids) is determined primarily by ionic strength but also to an extent by pH. The stability of iron-(hydr)oxide colloids (applicable to corrosion-product colloids) is determined by both ionic strength and pH.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.24.0A	Diffusion of Colloids in EBS	Colloidal particles, together with any associated actinides, that are sufficiently small may be transported through the EBS by diffusion.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.25.0A	Formation of Colloids (Waste-Form) by Co-Precipitation in EBS	Dissolved radionuclides and other ions may coprecipitate to form colloids. Coprecipitates may consist of radionuclides bound in the crystal lattice of a dominating mineral phase or may consist of radionuclides engulfed by a dominating mineral phase.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.1.09.26.0A	Gravitational Settling of Colloids in EBS	Over the relatively short transport distances within the waste package, colloidal particles may experience gravitational settling, thereby inhibiting transport.	Excluded low consequence	See Footnote
2.1.09.27.0A	Coupled Effects on Radionuclide Transport in EBS	Repository induced changes to the physical and chemical properties of the EBS and waste form may be important for evaluating radionuclide transport in the EBS. The existence of chemical gradients within the disposal system, resulting from repository material, waste emplacement, and corrosion products, may influence the transport of dissolved and colloidal species. This could include: geochemical reactions that move (pump) radionuclides; effects on advection, diffusion, and sorption within and through failed waste packages; and microbial and electrochemical effects.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.09.28.0A	Localized Corrosion on Waste Package Outer Surface Due to Deliquescence	Salt-containing dust, which could accumulate on the waste package surface during the preclosure ventilation period, can absorb moisture from the drift atmosphere, even at low relative humidity, dissolving the salt and creating concentrated aqueous solutions. This deliquescence process may result in localized surface chemistry that could cause penetration of the waste package outer barrier by localized corrosion.	Excluded low consequence	See Footnote
2.1.09.28.0B	Localized Corrosion on Drip Shield Surfaces Due to Deliquescence	Salt-containing dust, which could accumulate on the drip shield surface during the preclosure ventilation period, can absorb moisture from the drift atmosphere, even at low relative humidity, dissolving the salt and creating concentrated aqueous solutions. This deliquescence process may result in localized surface chemistry that could cause penetration of the drip shield surface by localized corrosion.	Excluded low probability	See Footnote
2.1.10.01.0A	Microbial Activity in EBS	Biological activity is important to consider because of the potential impact on aqueous chemical conditions within the waste and EBS. In deep subsurface environments, biological activity is limited to microbiological activity and may include effects of natural and anthropogenic bacteria (e.g., anaerobic, methanogenic, sulfate reducers, etc.), protozoans, yeast, viruses, and algae. This FEP addresses a broad range of effects of biological impacts, including the effects of microbes on corrosion of waste packages, cladding, and waste form; bioreduction of multivalent contaminants, metals, and sulfate; generation of organic complexants and gases as metabolic by-products; and the formation of biofilms and their impact on transport.	Excluded low consequence	See Footnote
2.1.11.01.0A	Heat Generation in EBS	Temperature in the waste and EBS will vary through time. Heat from radioactive decay will be the primary cause of temperature change, but other factors to be considered in determining the temperature history include the in-situ geothermal gradient; thermal properties of the rock, EBS, and waste materials; hydrologic effects; and the possibility of exothermic reactions. Considerations of the heat generated by radioactive decay should take different properties of different waste types, including DOE SNF, into account.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.11.02.0A	Non-Uniform Heat Distribution in EBS	Uneven heating and cooling at edges of the repository may lead to nonuniform thermal effects during both the thermal peak and the cool-down period.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-2
2.1.11.03.0A	Exothermic Reactions in the EBS	Exothermic reactions liberate heat and will alter the temperature of the disposal system and affect the properties of the repository and surrounding materials. Examples of possible exothermic reactions include oxidation of uranium metal fuels such as represented by N Reactor fuels and hydration of concrete used in the underground environment.	Excluded low consequence	See Footnote
2.1.11.05.0A	Thermal Expansion/Stress of In-Package EBS Components	Thermally induced stresses could alter the performance of the waste or EBS. For example, thermal stresses could cause the waste form to develop cracks and create pathways for preferential fluid flow and, thereby, accelerate degradation of the waste.	Excluded low consequence	See Footnote
2.1.11.06.0A	Thermal Sensitization of Waste Packages	Phase changes in waste package materials can result from long-term storage at moderately hot temperatures in the repository. Stress corrosion cracking, intergranular corrosion, or mechanical degradation may ensue.	Excluded low consequence	See Footnote
2.1.11.06.0B	Thermal Sensitization of Drip Shields	Phase changes in drip shield materials can result from long-term storage at moderately hot temperatures in the repository. Stress corrosion cracking, intergranular corrosion, or mechanical degradation may ensue.	Excluded low probability	See Footnote
2.1.11.07.0A	Thermal Expansion/Stress of In-Drift EBS Components	Repository heat at Yucca Mountain could result in thermally induced stress changes that would affect the mechanical and chemical evolution of the repository. These stress changes could affect the EBS components, thus causing the formation of pathways for groundwater flow through the EBS or altering and/or enhancing existing pathways. Relevant processes include changes in physical properties of the drip shields, waste packages, pallet, and invert.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.11.08.0A	Thermal Effects on Chemistry and Microbial Activity in the EBS	Temperature changes may affect chemical and microbial processes in the waste and EBS.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-3 Table 2.3.7-1
2.1.11.09.0A	Thermal Effects on Flow in the EBS	High temperatures in the EBS may influence seepage into, and flow within, the waste and EBS. Thermally-induced changes to fluid saturation and/or relative humidity could influence in-package chemistry. Thermal gradients in the repository could lead to localized accumulation of moisture. Wet zones could form below the areas of moisture accumulation.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-2
2.1.11.09.0B	Thermally-Driven Flow (Convection) in Waste Packages	Temperature differentials may result in convective flow in the EBS. Convective flow within the waste packages could influence in-package chemistry.	Excluded low consequence	See Footnote
2.1.11.09.0C	Thermally Driven Flow (Convection) in Drifts	Temperature differentials may result in convective flow in the EBS. Convective flow within the drifts could influence in-drift chemistry.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-2 Table 2.3.5-3
2.1.11.10.0A	Thermal Effects on Transport in EBS	Temperature changes in the repository may influence advection, diffusion, and sorption in the EBS. The Soret effect is a diffusion process caused by a thermal gradient. In liquids having both light and heavy molecules (or ions) and a temperature or thermal gradient, the heavier solute molecules tend to concentrate in the colder region. Temperature differences in the waste and EBS may result in a component of diffusive solute flux that is proportional to the temperature gradient.	Excluded low consequence	See Footnote
2.1.12.01.0A	Gas Generation (Repository Pressurization)	Gas generation in the repository might lead to pressurization of the repository, produce multiphase flow, and affect radionuclide transport. This FEP addresses repository pressurization.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.12.02.0A	Gas Generation (He) from Waste Form Decay	Helium (He) gas production will occur by alpha decay in the waste. Helium production might cause local pressure buildup in cracks in the fuel and in the void between fuel and cladding, leading to cladding and waste package failure.	Excluded low consequence	See Footnote
2.1.12.03.0A	Gas Generation (H_2) from Waste Package Corrosion	Gas generation can affect the mechanical behavior of the host rock and engineered barriers, chemical conditions, and fluid flow, and, as a result, the transport of radionuclides. Gas generation due to oxic corrosion of waste packages, cladding, and/or structural materials will occur at early times following closure of the repository. Anoxic corrosion may follow the oxic phase if all oxygen is depleted.	Excluded low consequence	See Footnote
2.1.12.04.0A	Gas Generation (CO_2, CH_4, H_2S) from Microbial Degradation	Microbes are known to produce inorganic acids, methane, organic byproducts, carbon dioxide, and other chemical species that could change the longevity of materials in the repository and the transport of radionuclides from the near-field. The rate of microbial gas production will depend on the nature of the microbial populations established, the prevailing conditions (temperature, pressure, geochemical conditions), and the organic or inorganic substrates present. Initial analysis indicates the most important source of nutrient in the Yucca Mountain Project repository will be metals. Other possible nutrients include cellulosic material, plastics, and synthetic materials. Minimal amounts of organics are mandated by regulation.	Excluded low consequence	See Footnote
2.1.12.06.0A	Gas Transport in EBS	Gas in the waste and EBS could affect the long-term performance of the disposal system. Radionuclides may be transported as gases or in gases. Gas bubbles may affect flow paths, and two-phase flow conditions may be important.	Excluded low consequence	See Footnote
2.1.12.07.0A	Effects of Radioactive Gases in EBS	Radioactive gases may exist or be produced in the repository. These gases may subsequently escape from the repository. Typical radioactive gases include ^{14}C (in $^{14}CO_2$ and $^{14}CH_4$ produced during microbial degradation), tritium, fission gases (argon, xenon, krypton), and radon.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.12.08.0A	Gas Explosions in EBS	Explosive gas mixtures could collect in the sealed repository. An explosion in the repository could have radiological consequences if the structure of the repository were damaged or near-field processes enhanced or inhibited.	Excluded low probability	See Footnote
2.1.13.01.0A	Radiolysis	Alpha, beta, gamma, and neutron irradiation of water can cause disassociation of molecules, leading to gas production and changes in chemical conditions (oxidation potential, pH, and concentration of reactive radicals).	Excluded low consequence	See Footnote
2.1.13.02.0A	Radiation Damage in EBS	Radiolysis due to the alpha, beta, gamma-ray, and neutron irradiation of water could result in enhancement of the radionuclide migration from the surface of a degraded waste form into groundwater. When radionuclides decay, the emitted high-energy particle could result in the production of radicals in the water or air surrounding the spent nuclear fuel. If these radicals migrate (diffuse) to the surface of the fuel, they may then enhance the degradation/corrosion rate of the fuel (UO_2). This effect would increase the dissolution rate for radionuclides from the fuel material (fuel matrix) into the groundwater. Strong radiation fields could lead to radiation damage to the waste forms (commercial SNF, DOE SNF, DOE HLW), waste packages, drip shield, seals, and surrounding rock.	Excluded low consequence	See Footnote
2.1.13.03.0A	Radiological Mutation of Microbes	Radiation fields could cause mutation of microorganisms, leading to unexpected chemical reactions and impacts.	Excluded low consequence	See Footnote
2.1.14.15.0A	In-Package Criticality (Intact Configuration)	The waste package internal structures and the waste form remain intact. If there is a breach (or are breaches) in the waste package that allows water to either accumulate or flow-through the waste package, then criticality could occur in situ.	Excluded low probability	See Footnote
2.1.14.16.0A	In-Package Criticality (Degraded Configurations)	The waste package internal structures and the waste form may degrade. If a potentially critical configuration (sufficient fissile material and neutron moderator, lack of neutron absorbers) develops, a criticality event could occur in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003).	Excluded low probability	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.14.17.0A	Near-Field Criticality	Near-field criticality could occur if fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3.3a).	Excluded low probability	See Footnote
2.1.14.18.0A	In-Package Criticality Resulting from a Seismic Event (Intact Configuration)	The waste package internal structures and the waste form remain intact either during or after a seismic disruptive event. If there is a breach (or are breaches) in the waste package that allow(s) water to either accumulate or flow through the waste package, then criticality could occur in situ.	Excluded low probability	See Footnote
2.1.14.19.0A	In-Package Criticality Resulting from a Seismic Event (Degraded Configurations)	Either during or as a result of a seismic disruptive event, the waste package internal structures and the waste form may degrade. If a critical configuration develops, criticality could occur in situ. Potential in situ critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figures 3.2a and 3.2b).	Excluded low probability	See Footnote
2.1.14.20.0A	Near-Field Criticality Resulting from a Seismic Event	Either during or as a result of a seismic disruptive event, near-field criticality could occur if fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3.3a).	Excluded low probability	See Footnote
2.1.14.21.0A	In-Package Criticality Resulting from Rockfall (Intact Configuration)	The waste package internal structures and the waste form remain intact either during or after a rockfall event. If there is a breach (or are breaches) in the waste package that allow(s) water to either accumulate or flow through the waste package, then criticality could occur in situ.	Excluded low probability	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.1.14.22.0A	In-Package Criticality Resulting from Rockfall (Degraded Configurations)	Either during or as a result of a rockfall event, the waste package internal structures and the waste form may degrade. If a critical configuration develops, criticality could occur in situ. Potential in situ critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figures 3.2a and 3.2b).	Excluded low probability	See Footnote
2.1.14.23.0A	Near-Field Criticality Resulting from Rockfall	Either during or as a result of a rockfall event, near-field criticality could occur if fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3.3a).	Excluded low probability	See Footnote
2.1.14.24.0A	In-Package Criticality Resulting from an Igneous Event (Intact Configuration)	The waste package internal structures and the waste form remain intact either during or after an igneous disruptive event. If there is a breach (or are breaches) in the waste package that allow(s) water to either accumulate or flow through the waste package, then criticality could occur in situ.	Excluded low probability	See Footnote
2.1.14.25.0A	In-Package Criticality Resulting from an Igneous Event (Degraded Configurations)	Either during or as a result of an igneous disruptive event, the waste package internal structures and the waste form may degrade. If a critical configuration develops, criticality could occur in situ. Potential in situ critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figures 3.2a and 3.2b).	Excluded low probability	See Footnote
2.1.14.26.0A	Near-Field Criticality Resulting from an Igneous Event	Either during or as a result of an igneous disruptive event, near-field criticality could occur if fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3.3a).	Excluded low probability	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.01.01.0A	Mechanical Effects of Excavation and Construction in the Near-Field	Excavation will produce some disturbance of the rocks surrounding the drifts due to stress relief. Stresses associated directly with excavation (e.g., boring and blasting operations) may also cause some changes in rock properties. Properties that may be affected include rock strength, fracture spacing and block size, and hydrologic properties such as permeability.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.3-1
2.2.01.01.0B	Chemical Effects of Excavation and Construction in the Near-Field	Excavation may result in chemical changes to the incoming groundwater and to the rock in the excavation disturbed zone.	Excluded low consequence	See Footnote
2.2.01.02.0A	Thermally-Induced Stress Changes in the Near-Field	Changes in host rock properties may result from thermal effects or other factors related to emplacement of the waste. Properties that may be affected include rock strength, fracture spacing and block size, and hydrologic properties such as permeability and sorption.	Excluded low consequence	See Footnote
2.2.01.02.0B	Chemical Changes in the Near-Field from Backfill	Changes in host rock properties may result from chemical effects of backfill. Properties that may be affected include permeability and sorption.	Excluded low Consequence	See Footnote
2.2.01.03.0A	Changes in Fluid Saturations in the Excavation Disturbed Zone	Fluid flow in the region near the repository may be affected by the presence of the excavation, waste, and EBS. Some dryout will occur during excavation and operations.	Excluded low consequence	See Footnote
2.2.01.04.0A	Radionuclide Solubility in the Excavation Disturbed Zone	Radionuclide solubility limits in the excavation-disturbed zone may differ from those in the EBS.	Excluded low consequence	See Footnote
2.2.01.05.0A	Radionuclide Transport in the Excavation Disturbed Zone	Radionuclide transport through the excavation disturbed zone may differ from transport in the EBS and the undisturbed host rock. Transport processes such as dissolution and precipitation, sorption, and colloid filtration should be considered.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.03.01.0A	Stratigraphy	Stratigraphic information is necessary information for the performance assessment. This information should include identification of the relevant rock units, soils and alluvium, and their thickness, lateral extents, and relationships to each other. Major discontinuities should be identified.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2 Table 2.3.8-1 Table 2.3.9-1
2.2.03.02.0A	Rock Properties of Host Rock and Other Units	Physical properties such as porosity and permeability of the relevant rock units, soils, and alluvium are necessary for the performance assessment. Possible heterogeneities in these properties should be considered. Questions concerning events and processes that may cause these physical properties to change over time are considered in other FEPs.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.1-1 Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2 Table 2.3.8-1 Table 2.3.9-1
2.2.06.01.0A	Seismic Activity Changes Porosity and Permeability of Rock	Seismic activity (fault displacement or vibratory ground motion) has a potential to change rock stresses and result in strains that affect flow properties in rock outside the excavation-disturbed zone. It could result in strains that alter the permeability in the rock matrix. These effects may decrease the transport times for potentially released radionuclides.	Excluded low consequence	See Footnote
2.2.06.02.0A	Seismic Activity Changes Porosity and Permeability of Faults	Seismic activity (fault displacement or vibratory ground motion) has a potential to produce jointed-rock motion and change stress and strains that alter the permeability along faults. This could result in reactivation of preexisting faults or generation of significant new faults, which could significantly change the flow and transport paths, alter or short-circuit the flow paths and flow distributions close to the repository, and/or create new pathways through the repository. These effects may decrease the transport times for potentially released radionuclides.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.06.02.0B	Seismic Activity Changes Porosity and Permeability of Fractures	Seismic activity (fault displacement or vibratory ground motion) has a potential to change stress and strains that alter the permeability along fractures. This could result in reactivation of preexisting fractures or generation of new fractures, which could significantly change the flow and transport paths, alter or short-circuit the flow paths and flow distributions close to the repository, and/or create new pathways through the repository. These effects may decrease the transport times for potentially released radionuclides.	Excluded low consequence	See Footnote
2.2.06.03.0A	Seismic Activity Alters Perched Water Zones	Strain caused by stress changes from tectonic or seismic events could alter the rock permeabilities that allow formation and persistence of perched-water zones.	Excluded low consequence	See Footnote
2.2.06.04.0A	Effects of Subsidence	Subsidence above the mined underground facility or other openings may affect the properties of the overlying rocks and surface topography. Changes in rock properties, such as enhanced permeability, may alter flow paths from the surface to the repository. Changes in surface topography may alter runoff and infiltration, and may perhaps create impoundments.	Excluded low consequence	See Footnote
2.2.06.05.0A	Salt Creep	Salt creep may lead to changes in the stress field, compaction of the waste packages, and consolidation of the long-term components of the sealing system.	Excluded low consequence	See Footnote
2.2.07.01.0A	Locally Saturated Flow at Bedrock/Alluvium Contact	In arid areas and particularly in areas with shallow soils, infiltration can descend to the alluvium/bedrock interface and then proceed along that interface as a saturated flow system distinct from the surface water flow and distinct from the local water table. This phenomenon usually requires that the permeability of the bedrock be considerably less than that of the overlying soils.	Excluded low consequence	See Footnote
2.2.07.02.0A	Unsaturated Groundwater Flow in the Geosphere	Groundwater flow occurs in unsaturated rocks in most locations above the water table at Yucca Mountain, including at the location of the repository. See related FEPs for discussions of specific issues related to unsaturated flow.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2 Table 2.3.8-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.07.03.0A	Capillary Rise in the UZ	Capillary rise involves the drawing up of water, above the water table or above locally saturated zones, in continuous pores of the unsaturated zone until the suction gradient is balanced by the gravitational pull downward.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.3-1
2.2.07.04.0A	Focusing of Unsaturated Flow (Fingers, Weeps)	Unsaturated flow can differentiate into zones of greater and lower saturation (fingers) that may persist as preferential flow paths. Heterogeneities in rock properties, including fractures and faults, may contribute to focusing. Focused flow may become locally saturated.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.3-1 Table 2.3.8-1
2.2.07.05.0A	Flow in the UZ from Episodic Infiltration	Episodic flow could occur in the unsaturated zone as a result of episodic infiltration. Episodic flow may affect radionuclide transport.	Excluded low consequence	See Footnote
2.2.07.06.0A	Episodic or Pulse Release from Repository	Episodic or pulse release of radionuclides from the repository and radionuclide transport in the unsaturated zone may occur both because of episodic flow into the repository, and because of pulse releases from failed waste packages.	Excluded low consequence	See Footnote
2.2.07.06.0B	Long-Term Release of Radionuclides from the Repository	The release of radionuclides from the repository may occur over a long period of time, as a result of the timing and magnitude of the waste packages and drip shield failures, waste form degradation, and radionuclide transport through the invert.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1 Table 2.3.8-1
2.2.07.07.0A	Perched Water Develops	Zones of perched water may develop above the water table. If these zones occur above the repository, they may affect unsaturated zone flow between the surface and the waste packages. If they develop below the repository, e.g., at the base of the Topopah Spring welded unit, they may affect flow pathways and radionuclide transport between the waste packages and the saturated zone.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.8-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.07.08.0A	Fracture Flow in the UZ	Fractures or other analogous channels may act as conduits for fluids to move into the subsurface to interact with the repository and as conduits for fluids to leave the vicinity of the repository and be conducted to the saturated zone. Water may flow through only a portion of the fracture network, including flow through a restricted portion of a given fracture plane.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2 Table 2.3.8-1
2.2.07.09.0A	Matrix Imbibition in the UZ	Water flowing in fractures or other channels in the unsaturated zone may be imbibed into the surrounding rock matrix. This may occur during steady flow, episodic flow, or into matrix pores that have been dried out during the thermal period.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-2 Table 2.3.8-1
2.2.07.10.0A	Condensation Zone Forms Around Drifts	Condensation of the two-phase flow generated by repository heat may form in the rock where the temperature drops below the local vaporization temperature. Waste package emplacement geometry and thermal loading may affect the scale at which condensation caps form (over waste packages, over panels, or over the entire repository), and the extent to which “shedding” will occur as water flows from the region above one drift to the region above another drift or into the rock between drifts.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.5-2
2.2.07.11.0A	Resaturation of Geosphere Dry-Out Zone	Following the peak thermal period, water in the condensation cap may flow downward into the drifts. Influx of cooler water from above, such as might occur from episodic flow, may accelerate return flow from the condensation cap by lowering temperatures below the condensation point. Percolating groundwater will also contribute to resaturation of the dryout zone. Vapor flow, as distinct from liquid flow by capillary processes, may also contribute.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.5-2 Table 2.3.5-3
2.2.07.12.0A	Saturated Groundwater Flow in the Geosphere	Groundwater flow in the saturated zone below the water table may affect long-term performance of the repository. The location, magnitude, and direction of flow under present and future conditions and the hydraulic properties of the rock are all relevant.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.07.13.0A	Water-Conducting Features in the SZ	Geologic features in the saturated zone may affect groundwater flow by providing preferred pathways for flow.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1
2.2.07.14.0A	Chemically-Induced Density Effects on Groundwater Flow	Chemically-induced spatial variation in groundwater density may affect groundwater flow.	Excluded low consequence	See Footnote
2.2.07.15.0A	Advection and Dispersion in the SZ	Advection and dispersion processes may affect radionuclide transport in the saturated zone.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1
2.2.07.15.0B	Advection and Dispersion in the UZ	Advection and dispersion processes may affect radionuclide transport in the unsaturated zone.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.8-1
2.2.07.16.0A	Dilution of Radionuclides in Groundwater	Dilution due to mixing of contaminated and uncontaminated water may affect radionuclide concentrations in groundwater during transport in the saturated zone and during pumping at a withdrawal well.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1
2.2.07.17.0A	Diffusion in the SZ	Molecular diffusion processes may affect radionuclide transport in the saturated zone.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.07.18.0A	Film Flow into the Repository	Water may enter waste emplacement drifts by a film flow process. This differs from the traditional view of flow in a capillary network where the wetting phase exclusively occupies capillaries with apertures smaller than some level defined by the capillary pressure. A film flow process could allow water to enter a waste emplacement drift at nonzero capillary pressure. Dripping into the drifts could also occur through collection of the film flow on the local minima of surface roughness features along the crown of the drift.	Included 10 CFR 63.311 (proposed) 10 CFR 63.331	Table 2.3.3-1
2.2.07.19.0A	Lateral Flow from Solitario Canyon Fault Enters Drifts	Water movement down Solitario Canyon Fault could enter waste emplacement drifts through lateral flow mechanisms in the Topopah Spring welded hydrogeologic unit. This percolation pathway is more likely to transmit episodic transient flow to waste emplacement locations due to the major fault pathway through the overlying units.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1
2.2.07.20.0A	Flow Diversion Around Repository Drifts	Flow in unsaturated rock tends to be diverted by openings such as waste emplacement drifts due to the effects of capillary forces. The resulting diversion of flow could have an effect on seepage into the repository. Flow diversion around the drift openings could also lead to the development of a zone of lower flow rates and low saturation beneath the drift, known as the drift shadow.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.5-2
2.2.07.21.0A	Drift Shadow Forms Below Repository	Flow in unsaturated rock tends to be diverted by openings such as waste emplacement drifts due to the effects of capillary forces. Flow diversion around the drift openings could lead to the development of a zone of lower flow rates and low saturation beneath the drift, known as the drift shadow. Radionuclide transport rates through the unsaturated rock may be dependent on whether or not radionuclide releases occur from drifts that are underlain by a drift shadow.	Excluded low consequence	See Footnote
2.2.08.01.0A	Chemical Characteristics of Groundwater in the SZ	Chemistry and other characteristics of groundwater in the saturated zone may affect groundwater flow and radionuclide transport of dissolved and colloidal species. Groundwater chemistry and other characteristics, including temperature, pH, Eh, ionic strength, and major ionic concentrations, may vary spatially throughout the system as a result of different rock mineralogy.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.08.01.0B	Chemical Characteristics of Groundwater in the UZ	Chemistry and other characteristics of groundwater in the unsaturated zone may affect groundwater flow and radionuclide transport of dissolved and colloidal species. Groundwater chemistry and other characteristics, including temperature, pH, Eh, ionic strength, and major ionic concentrations, may vary spatially throughout the system as a result of different rock mineralogy. The chemistry of the groundwater in the unsaturated zone will affect the drift seepage composition and thereby the potential for localized corrosion on the waste package corrosion barrier.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-1 Table 2.3.8-1
2.2.08.03.0A	Geochemical Interactions and Evolution in the SZ	Groundwater chemistry and other characteristics, including temperature, pH, Eh, ionic strength, and major ionic concentrations, may change through time, as a result of the evolution of the disposal system or from mixing with other waters. Geochemical interactions may lead to dissolution and precipitation of minerals along the groundwater flow path, affecting groundwater flow, rock properties, and sorption of radionuclides. Effects on hydrologic flow properties of the rock, radionuclide solubilities, sorption processes, and colloidal transport are relevant. Kinetics of chemical reactions should be considered in the context of the time scale of concern.	Excluded low consequence	See Footnote
2.2.08.03.0B	Geochemical Interactions and Evolution in the UZ	Groundwater chemistry and other characteristics, including temperature, pH, Eh, ionic strength, and major ionic concentrations, may change through time, as a result of the evolution of the disposal system or from mixing with other waters. Geochemical interactions may lead to dissolution and precipitation of minerals along the groundwater flow path, affecting groundwater flow, rock properties, and sorption of radionuclides. Effects on hydrologic flow properties of the rock, radionuclide solubilities, sorption processes, and colloidal transport are relevant. Kinetics of chemical reactions should be considered in the context of the time scale of concern.	Excluded low consequence	See Footnote
2.2.08.04.0A	Re-Dissolution of Precipitates Directs more Corrosive Fluids to Waste Packages	Redissolution of precipitates that have plugged pores as a result of evaporation of groundwater in the dryout zone, may produce a pulse of fluid reaching the waste packages when gravity-driven flow resumes, which is more corrosive than the original fluid in the rock.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.08.05.0A	Diffusion in the UZ	Molecular diffusion processes may affect radionuclide transport in the unsaturated zone. This includes osmotic processes in response to chemical gradients.	Excluded low consequence	See Footnote
2.2.08.06.0A	Complexation in the SZ	Complexing agents such as carbonate, fluoride, and humic and fulvic acids present in natural groundwaters could affect radionuclide transport in the saturated zone.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1
2.2.08.06.0B	Complexation in the UZ	Complexing agents such as humic and fulvic acids present in natural groundwaters could affect radionuclide transport in the unsaturated zone.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.8-1
2.2.08.07.0A	Radionuclide Solubility Limits in the SZ	Solubility limits for radionuclides are different in saturated zone groundwater than in the water in the unsaturated zone or in the waste and EBS.	Excluded low consequence	See Footnote
2.2.08.07.0B	Radionuclide Solubility Limits in the UZ	Solubility limits for radionuclides may be different in unsaturated zone groundwater than in the water in the waste and EBS.	Excluded low consequence	See Footnote
2.2.08.07.0C	Radionuclide Solubility Limits in the Biosphere	Solubility limits for radionuclides may be different in the biosphere pathways than in the water in the saturated zone.	Excluded low consequence	See Footnote
2.2.08.08.0A	Matrix Diffusion in the SZ	Matrix diffusion is the process by which radionuclides and other species transported in the saturated zone by advective flow in fractures or other pathways move into the matrix of the porous rock by diffusion. Matrix diffusion can be a very efficient retarding mechanism, especially for strongly sorbed radionuclides, due to the increase in rock surface accessible to sorption.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.08.08.0B	Matrix Diffusion in the UZ	Matrix diffusion is the process by which radionuclides and other species transported in the unsaturated zone by advective flow in fractures or other pathways move into the matrix of the porous rock by diffusion. This includes osmotic processes in response to chemical gradients. Matrix diffusion can be a very efficient retarding mechanism, especially for strongly sorbed radionuclides, due to the increase in rock surface accessible to sorption.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.8-1
2.2.08.09.0A	Sorption in the SZ	Sorption of dissolved and colloidal radionuclides in the saturated zone can occur on the surfaces of both fractures and matrix in rock or soil along the transport path. Sorption may be reversible or irreversible, and it may occur as a linear or nonlinear process. Sorption kinetics and the availability of sites for sorption should be considered. Sorption is a function of the radioelement type, mineral type, and groundwater composition.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1
2.2.08.09.0B	Sorption in the UZ	Sorption of dissolved and colloidal radionuclides in the unsaturated zone can occur on the surfaces of both fractures and matrix in rock or soil along the transport path. Sorption may be reversible or irreversible, and it may occur as a linear or nonlinear process. Sorption kinetics and the availability of sites for sorption should be considered. Sorption is a function of the radioelement type, mineral type, and groundwater composition.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.8-1
2.2.08.10.0A	Colloidal Transport in the SZ	Radionuclides may be transported in groundwater in the saturated zone as colloidal species. Types of colloids include true colloids, pseudo colloids, and microbial colloids.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1
2.2.08.10.0B	Colloidal Transport in the UZ	Radionuclides may be transported in groundwater in the unsaturated zone as colloidal species. Types of colloids include true colloids, pseudo colloids, and microbial colloids.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.8-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.08.11.0A	Groundwater Discharge to Surface within the Reference Biosphere	Radionuclides transported in groundwater as solutes or solid materials (colloids) from the far field may discharge at specific “entry” points that are within the reference biosphere. Natural surface discharge points, including those resulting from water table or capillary rise, may be surface water bodies (rivers, lakes), springs, wetlands, holding ponds, or unsaturated soils.	Excluded low consequence	See Footnote
2.2.08.12.0A	Chemistry of Water Flowing into the Drift	Inflowing water chemistry may be used in analysis or modeling that requires initial water chemistry in the drift. Chemistry of water flowing into the drift is affected by initial water chemistry in the rock, mineral and gas composition in the rock, and thermal-hydrologic-chemical processes in the rock.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.5-1
2.2.08.12.0B	Chemistry of Water Flowing into the Waste Package	Inflowing water chemistry may be used in analysis or modeling that requires initial water chemistry in the waste package.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.7-1
2.2.09.01.0A	Microbial Activity in the SZ	Microbial activity in the saturated zone may affect radionuclide mobility in rock and soil through colloidal processes, by influencing the availability of complexing agents, or by influencing groundwater chemistry.	Excluded low consequence	See Footnote
2.2.09.01.0B	Microbial Activity in the UZ	Microbial activity in the unsaturated zone may affect radionuclide mobility in rock and soil through colloidal processes, by influencing the availability of complexing agents, or by influencing groundwater chemistry. Changes in microbial activity could be caused by the response of the soil zone to changes in climate.	Excluded low consequence	See Footnote
2.2.10.01.0A	Repository-Induced Thermal Effects on Flow in the UZ	Thermal effects in the geosphere could affect the long-term performance of the disposal system, including effects on groundwater flow (e.g., density-driven flow), mechanical properties, and chemical effects in the unsaturated zone.	Excluded low consequence	See Footnote
2.2.10.02.0A	Thermal Convection Cell Develops in SZ	Thermal effects due to waste emplacement result in convective flow in the saturated zone beneath the repository.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.10.03.0A	Natural Geothermal Effects on Flow in the SZ	The existing geothermal gradient, and spatial or temporal variability in that gradient, may affect groundwater flow in the saturated zones.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1
2.2.10.03.0B	Natural Geothermal Effects on Flow in the UZ	The existing geothermal gradient, and spatial or temporal variability in that gradient, may affect groundwater flow in the unsaturated zone.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-2
2.2.10.04.0A	Thermal-mechanical Stresses Alter Characteristics of Fractures Near Repository	Heat from the waste causes thermal expansion of the surrounding rock, generating changes in the stress field that may change the properties (both hydrologic and mechanical) of fractures in the rock. Cooling following the peak thermal period will also change the stress field, further affecting fracture properties near the repository.	Excluded low consequence	See Footnote
2.2.10.04.0B	Thermal-mechanical Stresses Alter Characteristics of Faults Near Repository	Heat from the waste causes thermal expansion of the surrounding rock, generating changes to the stress field that may change the properties (both hydrologic and mechanical) in and along faults. Cooling following the peak thermal period will also change the stress field, further affecting fault properties near the repository.	Excluded low consequence	See Footnote
2.2.10.05.0A	Thermal-mechanical Stresses Alter Characteristics of Rocks Above and Below the Repository	Thermal-mechanical compression at the repository may produce tension fracturing in the Paintbrush nonwelded tuff and other units above the repository. These fractures may alter unsaturated zone flow between the surface and the repository. Extreme fracturing may propagate to the surface, affecting infiltration. Thermal fracturing in rocks below the repository may affect flow and radionuclide transport to the saturated zone.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.10.06.0A	Thermal-chemical Alteration in the UZ (Solubility, Speciation, Phase Changes, Precipitation/ Dissolution)	Thermal effects may affect radionuclide transport directly, by causing changes in radionuclide speciation and solubility in the unsaturated zone, or indirectly, by causing changes in the host rock mineralogy that affect the flow path. Relevant processes include volume effects associated with silica phase changes, precipitation and dissolution of fracture-filling minerals (including silica and calcite), and alteration of zeolites and other minerals to clays.	Excluded low consequence	See Footnote
2.2.10.07.0A	Thermal-chemical Alteration of the Calico Hills Unit	Fracture pathways in the Calico Hills may be altered by the thermal and chemical properties of the water flowing out of the repository.	Excluded low consequence	See Footnote
2.2.10.08.0A	Thermal-chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/ Dissolution)	Thermal effects may affect radionuclide transport directly by causing changes in radionuclide speciation and solubility in the saturated zone, or, indirectly, by causing changes to host rock mineralogy that affect the flow path. Relevant processes include volume effects associated with silica phase changes, precipitation and dissolution of fracture filling minerals (including silica and calcite), and alteration of zeolites and other minerals to clays.	Excluded low consequence	See Footnote
2.2.10.09.0A	Thermal-chemical Alteration of the Topopah Spring Basal Vitrophyre	Heating the Topopah Spring basal vitrophyre with available water may cause alteration of the glasses to clays and zeolites. Possible effects include volume increases that plug fractures, changes in flow paths, creation of perched water zones, and an increase in the sorptive properties of the unit.	Excluded low consequence	See Footnote
2.2.10.10.0A	Two-Phase Buoyant Flow/Heat Pipes	Heat from waste can generate two-phase buoyant flow. The vapor phase (water vapor) could escape from the mountain. A heat pipe consists of a system for transferring energy between a hot and a cold region (source and sink respectively) using the heat of vaporization and movement of the vapor as the transfer mechanism. Two-phase circulation continues until the heat source is too weak to provide the thermal gradients required to drive it. Alteration of the rock adjacent to the drift may include dissolution that maintains the permeability necessary to support the circulation (as inferred for some geothermal systems).	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.5-2

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.10.11.0A	Natural Air Flow in the UZ	Natural convective air circulation has been observed at a borehole at the top of the mountain. Repository heat may increase this flow.	Excluded low consequence	See Footnote
2.2.10.12.0A	Geosphere Dry-Out Due to Waste Heat	Repository heat evaporates water from the unsaturated zone rocks near the drifts as the temperature exceeds the vaporization temperature. This zone of reduced water content (reduced saturation) migrates outward during the heating phase (about the first 1,000 years) and then migrates back to the waste packages as heat diffuses throughout the mountain and the radioactive sources decay. This FEP addresses the effects of dryout within the rocks.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2
2.2.10.13.0A	Repository-Induced Thermal Effects on Flow in the SZ	Thermal effects in the geosphere could affect the long-term performance of the disposal system, including effects on groundwater flow (e.g., density-driven flow), mechanical properties, and chemical effects in the saturated zone.	Excluded low consequence	See Footnote
2.2.10.14.0A	Mineralogic Dehydration Reactions	Mineralogic dehydration reactions release water affecting hydrologic conditions. Dehydration of zeolites below the repository may lead to large-scale volume changes affecting flow and/or drift stability.	Excluded low consequence	See Footnote
2.2.11.01.0A	Gas Effects in the SZ	Pressure variations due to gas generation may affect flow patterns and contaminant transport in the saturated zone. Degassing could affect flow and transport of gaseous contaminants. Potential gas sources include degradation of repository components and naturally occurring gases from clathrates, microbial degradation of organic material, or deep gases in general.	Excluded low consequence	See Footnote
2.2.11.02.0A	Gas Effects in the UZ	Pressure variations due to gas generation may affect flow patterns and contaminant transport in the unsaturated zone or may intrude into the repository. Degassing could affect flow and transport of gaseous contaminants. Gases could also affect other contaminants if water flow is driven by large gas bubbles forming in the repository. Potential gas sources include degradation of repository components and naturally occurring gases from clathrates, microbial degradation of organic material, or deep gases in general.	Excluded low consequence	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.11.03.0A	Gas Transport in Geosphere	Gas released from the drifts and gas generated in the near-field rock will flow through fracture systems in the near-field rock and in the geosphere. Certain gaseous or volatile radionuclides may be able to migrate through the far-field faster than the groundwater advection rate.	Excluded low consequence	See Footnote
2.2.12.00.0A	Undetected Features in the UZ	Undetected features in the unsaturated zone portion of the geosphere can affect long-term performance of the disposal system. Undetected but important features may be present, and may have significant impacts. These features include unknown active fracture zones, inhomogeneities, faults and features connecting different zones of rock, different geometries for fracture zones, and induced fractures due to the construction or presence of the repository.	Excluded low consequence	See Footnote
2.2.12.00.0B	Undetected Features in the SZ	Undetected features in the saturated zone portion of the geosphere can affect long-term performance of the disposal system. Undetected but important features may be present, and may have significant impacts. These features include unknown active fracture zones, inhomogeneities, faults and features connecting different zones of rock, and different geometries for fracture zones.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.9-1
2.2.14.09.0A	Far-Field Criticality	Far-field criticality could occur if fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3.3.b).	Excluded low probability	See Footnote
2.2.14.10.0A	Far-Field Criticality Resulting from a Seismic Event	Either during, or as a result of a seismic disruptive event, far-field criticality could occur if fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3.3b).	Excluded low probability	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.2.14.11.0A	Far-Field Criticality Resulting from Rockfall	Either during or as a result of a rockfall event, far-field criticality could occur if fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3.3b).	Excluded low probability	See Footnote
2.2.14.12.0A	Far-Field Criticality Resulting from an Igneous Event	Either during or as a result of an igneous disruptive event, far-field criticality could occur if fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3.3b).	Excluded low probability	See Footnote
2.3.01.00.0A	Topography and Morphology	This FEP is related to the topography and surface morphology of the disposal region. Topographical features include outcrops and hills, water-filled depressions, wetlands, recharge areas and discharge areas. Topography, precipitation, and surficial permeability distribution in the system will determine the flow boundary conditions (i.e., location and amount of recharge and discharge in the system).	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.1-1
2.3.02.01.0A	Soil Type	Soil type is determined by many different factors (e.g., formative process, geology, climate, vegetation, land use). The physical and chemical attributes of the surficial soils (such as organic matter content and pH) may influence the mobility of radionuclides.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.3.02.02.0A	Radionuclide Accumulation in Soils	Radionuclide accumulation in soils may occur as a result of upwelling of contaminated groundwater (leaching, evaporation at discharge location), deposition of contaminated water or particulates (irrigation water, runoff), and/or atmospheric deposition.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.3.02.03.0A	Soil and Sediment Transport in the Biosphere	Contaminated sediments can be transported to and through the biosphere by surface runoff and fluvial processes, and, to a lesser extent, by aeolian processes and bioturbation. Sediment transport and redistribution may cause concentration or dilution of radionuclides in the biosphere.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.3.04.01.0A	Surface Water Transport and Mixing	Radionuclides released from an underground repository might enter the biosphere through discharge of deep groundwater into a lake or river. Transport and mixing within the surface water bodies affects the subsequent behavior and transport of radionuclides in the biosphere. Transport and mixing includes dilution, sedimentation, aeration, streamflow, and river meander.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.3.06.00.0A	Marine Features	This FEP addresses marine and coastal features and processes. Processes include erosion, sedimentation, deposition, sea-level change, and storms.	Excluded low consequence	See Footnote
2.3.09.01.0A	Animal Burrowing/ Intrusion	Burrowing animals may intrude into the repository, promoting release and spread of contamination. Burrowing animals may also contact or ingest contaminated soil.	Excluded low consequence	See Footnote
2.3.11.01.0A	Precipitation	Precipitation is an important control on the amount of infiltration, flow in the unsaturated zone, seepage into the repository, and groundwater recharge. It transports solutes with it as it flows downward through the subsurface or escapes as runoff. Precipitation influences agricultural practices of the receptor. The amount of precipitation depends on climate.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.1-1 Table 2.3.2-1 Table 2.3.10-1
2.3.11.02.0A	Surface Runoff and Evapotranspiration	Surface water runoff and evapotranspiration are components in the water balance, together with precipitation, infiltration, and change in soil water storage. Surface runoff produces erosion, and can feed washes, arroyos, and impoundments, where flooding may lead to increased recharge. Evapotranspiration removes water from soil and rock by evaporation and transpiration via plant root water uptake.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.1-1 Table 2.3.2-1
2.3.11.03.0A	Infiltration and Recharge	Infiltration into the subsurface provides a boundary condition for groundwater flow in the unsaturated zone. The amount and location of the infiltration influences the amount of seepage entering the drifts; and the amount and location of recharge influences the height of the water table, the hydraulic gradient, and therefore specific discharge. Different sources of infiltration could change the composition of groundwater passing through the repository. Mixing of these waters with other groundwaters could result in mineral precipitation, dissolution, and altered chemical gradients in the subsurface.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.1-1 Table 2.3.2-1 Table 2.3.3-1 Table 2.3.5-1 Table 2.3.5-2

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.3.11.04.0A	Groundwater Discharge to Surface Outside the Reference Biosphere	Radionuclides transported in groundwater as solutes or solid materials (colloids) from the far field may discharge at specific "entry" points that are outside the reference biosphere. Natural surface discharge points, including those resulting from water table or capillary rise, may be surface water bodies (rivers, lakes), springs, wetlands, holding ponds, or unsaturated soils.	Excluded by Regulation	See Footnote
2.3.13.01.0A	Biosphere Characteristics	The principal components, conditions, or characteristics of the biosphere system can influence radionuclide transport and affect the long-term performance of the disposal system. These include the characteristics of the reference biosphere such as climate, soils and microbes, flora and fauna, and their influences on human activities.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.3.13.02.0A	Radionuclide Alteration During Biosphere Transport	Once in the biosphere, radionuclides may be transported and transferred through and between different compartments of the biosphere. Temporally- and spatially-dependent physical and chemical environments in the biosphere may lead to alteration of both the physical and chemical properties of the radionuclides as they move through or between the different compartments of the biosphere. These alterations could consequently control exposure to the human population.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.3.13.03.0A	Effects of Repository Heat on the Biosphere	Heat released from radioactive decay of the waste may increase the temperatures at the surface above the repository. This could result in local or extensive changes in the ecological characteristics.	Excluded low consequence	See Footnote
2.3.13.04.0A	Radionuclide Release Outside the Reference Biosphere	Radionuclide releases outside the reference biosphere can occur. This could include areas surrounding distant springs and surface water bodies (such as at Ash Meadows), remote natural outfalls, discharge areas such as playas (e.g., Franklin Playa), or forests, grasslands, or wetlands that occur in isolated areas in the region. This might also include withdrawal from wells in remote areas. Radionuclide accumulation could occur in these areas. Sediment transport and redistribution may cause concentration or dilution of radionuclides. Flora and fauna in these areas may be exposed and radionuclides be bioaccumulated and enter the food chain. Intermittent use of these areas by humans may also lead to exposure.	Excluded by Regulation	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.4.01.00.0A	Human Characteristics (Physiology, Metabolism)	This FEP addresses human characteristics. These include physiology, metabolism, and variability among individual humans.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.4.04.01.0A	Human Lifestyle	Human lifestyle, including everyday household activities and leisure activities, will influence the critical exposure pathways to humans.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.4.07.00.0A	Dwellings	This FEP addresses human dwellings, and the ways in which dwellings might affect human exposures. Exposure pathways might be influenced by building materials and location.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.4.08.00.0A	Wild and Natural Land and Water Use	Human uses of wild and natural lands (forests, bush, coastlines) and water (lakes, rivers, oceans) may affect the long-term performance of the repository. Wild and natural land use will be primarily controlled by natural factors (topography, climate, etc.).	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.4.09.01.0A	Implementation of New Agricultural Practices or Land Use	Agricultural land use depends on many interrelated factors including climate, geology, topography, human lifestyle, and economics. Land use may include practices such as traditional crop farming, greenhouses, and hydroponics. Agricultural practices have the potential for radionuclide transfer through the food chain and may influence alternate pathways. Changes in current agricultural practices could change the significance of various exposure pathways.	Excluded by Regulation	See Footnote
2.4.09.01.0B	Agricultural Land Use and Irrigation	Agricultural areas exist near Yucca Mountain, particularly in the direction of groundwater flow. Current practices include irrigation, plowing, fertilization, crop storage, and soil modification and amendment. Existing practices may play a significant role in determining exposure pathways and dose.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
2.4.09.02.0A	Animal Farms and Fisheries	Domestic livestock or fish could become contaminated through the intake of contaminated feed, water, or soil. Such contamination could then enter the food chain.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
2.4.10.00.0A	Urban and Industrial Land and Water Use	Urban and industrial uses of land and water (industry, urban development, earthworks, energy production, etc.) may affect the long-term performance of the repository. Urban and industrial land use will be controlled by both natural factors (topography, climate, etc.) and human factors (economics, population density, etc.).	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
3.1.01.01.0A	Radioactive Decay and Ingrowth	Radioactivity is the spontaneous disintegration of an unstable atomic nucleus that results in the emission of subatomic particles. Radioactive species (isotopes) of a given element are known as radionuclides. Radioactive decay of the fuel in the repository changes the radionuclide content in the fuel with time and generates heat. Radionuclide quantities in the system at any time are the result of the radioactive decay and the ingrowth of decay products as a consequence of that decay. Over the 10,000-year performance period, these processes will produce decay products that need to be considered in order to adequately evaluate the release and transport of radionuclides to the accessible environment.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.10-1 Table 2.3.7-1 Table 2.3.8-1 Table 2.3.9-1
3.2.07.01.0A	Isotopic Dilution	Mixing or dilution of the radioactive species from the waste with species of the same element from other sources (i.e., stable and/or naturally occurring isotopes of the same element) could lead to a reduction of the radiological consequences.	Excluded low consequence	See Footnote
3.2.10.00.0A	Atmospheric Transport of Contaminants	Atmospheric transport includes radiotoxic and chemotoxic species in the air as gas, vapor, particulates, or aerosol. Transport processes include wind, plowing and irrigation, degassing, saltation, and precipitation.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
3.3.01.00.0A	Contaminated Drinking Water, Foodstuffs and Drugs	This FEP addresses human diet and fluid intake. Consumption of food, water, soil, drugs, etc., will affect human exposure to radionuclides. Other influences include filtration of water, dilution of diet with uncontaminated food, and food preparation techniques.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.10-1
3.3.02.01.0A	Plant Uptake	Uptake and accumulation of contaminants by plants could affect potential exposure pathways. Plant uptake from contaminated soils and irrigation water is possible. Particulate deposition onto plant surfaces is also possible. These plants may be used as feed for livestock and/or consumed directly by humans.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
3.3.02.02.0A	Animal Uptake	Livestock may accumulate radionuclides as a result of ingestion (water, feed and soil/sediment) and inhalation (aerosols and particulates). Depending on the livestock, they may be used for human consumption directly, or their produce (milk, eggs, etc.) may be consumed.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
3.3.02.03.0A	Fish Uptake	Uptake and bioaccumulation of contaminants in aquatic organisms could affect potential exposure pathways.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
3.3.03.01.0A	Contaminated Nonfood Products and Exposure	Contaminants may be concentrated in various products: clothing (e.g., hides, leather, linen, wool); furniture (e.g., wood, metal); building materials (e.g., stone, clay for bricks, wood, dung); fuel (e.g., peat), tobacco, pets.	Included 10 CFR 63.311 10 CFR 63.321 (proposed)	Table 2.3.10-1
3.3.04.01.0A	Ingestion	Ingestion is human exposure to repository-derived radionuclides through eating contaminated foodstuffs or drinking contaminated water.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.10-1

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
3.3.04.02.0A	Inhalation	Inhalation pathways for repository-derived radionuclides should be considered. Two possible pathways are: inhalation of gases and vapors emanating directly from the ground after transport through the far-field; and inhalation of suspended, contaminated particulate matter (e.g., decay products of radon, dust, smoke, pollen, and soil particles).	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
3.3.04.03.0A	External Exposure	External exposure is human exposure to repository-derived radionuclides by contact, use, or exposure to contaminated materials.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed)	Table 2.3.10-1
3.3.05.01.0A	Radiation Doses	The radiation dose is calculated from exposure rates (external, inhalation, and ingestion) and dose coefficients. The latter are based upon radiation type, human metabolism, metabolism of the element of concern in the human body, and duration of exposure.	Included 10 CFR 63.311 (proposed) 10 CFR 63.321 (proposed) 10 CFR 63.331	Table 2.3.10-1
3.3.06.00.0A	Radiological Toxicity and Effects	This FEP addresses the estimation of human health effects resulting from radiation doses.	Excluded by Regulation	See Footnote
3.3.06.01.0A	Repository Excavation	Excavation of the repository and/or its contents may result in the production of tailings, which may subsequently release toxic contaminants.	Excluded by Regulation	See Footnote
3.3.06.02.0A	Sensitization to Radiation	Human and other organisms may become sensitized to radiation exposure so that its effects are more severe.	Excluded by Regulation	See Footnote
3.3.07.00.0A	Nonradiological Toxicity and Effects	This FEP addresses the estimation of human health effects resulting from the nonradiological toxicity of the waste.	Excluded by Regulation	See Footnote

Table 2.2-5. Complete Listing of FEPs Considered (Continued)

No.	FEP Name	FEP Description	Screening Decision	Section/Table or Location Where Technical Basis Is Summarized
3.3.08.00.0A	Radon and Radon Decay Product Exposure	This FEP addresses human exposure to radon and radon decay products. ^{226}Ra occurs in nuclear fuel waste and it gives rise to ^{222}Rn gas, the radioactive decay products of which can result in radiation doses to humans upon inhalation.	Included	Table 2.3.10-1

NOTE: Further discussion of the technical bases for the screening decisions are covered in detail in the *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008a).

Table 2.2-6. Human Intrusion—Related Features, Events, and Processes Included in the Performance Assessment to Demonstrate Compliance with Proposed 10 CFR 63.321

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
1.4.02.02.0A Inadvertent Human Intrusion	Humans could accidentally intrude into the repository. Without appropriate precautions, intruders could experience high radiation exposures. Moreover, containment may be left damaged, which could increase radionuclide release rates to the biosphere. Inadvertent human intrusion might occur during scientific, mineral or geothermal exploration.	The approach to addressing potential future human intrusion into the Yucca Mountain repository is discussed in proposed Subpart E of 10 CFR Part 63 (Technical Criteria). In particular, in discussing institutional controls, 10 CFR 63.102(k) provides in part that: …because it is not possible to make scientifically sound forecasts of the long-term reliability of institutional controls, it is not appropriate to include consideration of human intrusion into a fully risk-based performance assessment for purposes of evaluating the ability of the geologic repository to achieve the performance objective at § 63.113(b). Hence, human intrusion is addressed in a stylized manner… Further, in discussing the human intrusion analysis, 10 CFR 63.102(l) provides, in part that: Although the consequences of an assumed intrusion event would be a separate analysis, the analysis is similar to the performance assessment required by § 63.113(b) but subject to specific requirements for evaluation of human intrusion specified at §§ 63.321, 63.322 and 63.342… Therefore, an assessment of human intrusion is required to demonstrate compliance with the individual protection standard for human intrusion (proposed 10 CFR 63.321), but human intrusion does not require consideration within the demonstration of compliance with the individual protection standard after permanent closure (proposed 10 CFR 63.311) or within the demonstration of compliance with the groundwater protection standards (10 CFR 63.331). The approach to assessing human intrusion is set out in proposed Subpart L of 10 CFR Part 63 (Postclosure Public Health and Environmental Standards), and proposed 10 CFR Part 63. A definition of human intrusion is provided at 10 CFR 63.302, the individual protection standard for human intrusion is provided at proposed 10 CFR 63.321, and the approach to evaluating a human intrusion scenario is specified at 10 CFR 63.322, as discussed below. Human intrusion is defined as follows: Human intrusion means breaching of any portion of the Yucca Mountain disposal system, within the repository footprint, by any human activity. Future human intrusion may be intentional and deliberate or may be inadvertent and accidental. The supplementary discussion in the preamble to 40 CFR Part 197 clarifies the point that consideration of deliberate human intrusion in the TSPA is not intended, as discussed in detail in FEP 1.4.02.01.0A (Deliberate human intrusion). Consideration of human intrusion into the repository is limited to inadvertent intrusion.

Table 2.2-6. Human Intrusion—Related Features, Events, and Processes Included in the Performance Assessment to Demonstrate Compliance with Proposed 10 CFR 63.321 (Continued)

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
1.4.02.02.0A Inadvertent Human Intrusion (Continued)		Inadvertent human intrusions are considered within the context of the regulatory requirements to demonstrate compliance with the human intrusion standard. Proposed 10 CFR 63.321 states the following: (a) DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion (see § 63.322) could occur without recognition by the drillers. (b) DOE must demonstrate that there is a reasonable expectation that the reasonably maximally exposed individual receives, as a result of human intrusion, no more than the following annual dose: (1) 0.15 mSv (15 mrem) for 10,000 years following disposal; and (2) 3.5 mSv (350 mrem) after 10,000 years, but within the period of geologic stability. (c) DOE's analysis must include all potential environmental pathways of radionuclide transport and exposure, subject to the requirements at § 63.322. The assessment of inadvertent human intrusion is based on an evaluation of the dose resulting from a stylized human intrusion drilling scenario. This approach is documented in *Total System Performance Assessment Model /Analysis for the License Application* (SNL 2008b, Section 6.7) to demonstrate that the repository design will exhibit a measure of resilience against a typical human intrusion scenario. The scenario is not intended to represent all forms of human intrusion that could affect the repository. The stylized scenario for human intrusion makes use of the following assumptions (10 CFR 63.322): (a) There is a single human intrusion as a result of exploratory drilling for ground water; (b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository; (c) The drillers use the common techniques and practices that are currently employed in exploratory drilling for ground water in the region surrounding Yucca Mountain; (d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole; (e) No particulate waste material falls into the borehole;

Table 2.2-6. Human Intrusion—Related Features, Events, and Processes Included in the Performance Assessment to Demonstrate Compliance with Proposed 10 CFR 63.321 (Continued)

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
1.4.02.02.0A Inadvertent Human Intrusion (Continued)		(f) The exposure scenario includes only those radionuclides transported to the saturated zone by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the saturated zone); and (g) No releases are included which are caused by unlikely natural processes and events. In particular, TSPA evaluation of the earliest time at which a waste package is expected to be breached is discussed in Section 6.7.2 of *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008b. Section 6.7.2.1 (SNL 2008b) describes the analysis of drip shield and waste package degradation for this scenario, Section 6.7.2.2 (SNL 2008b) describes unlikely events-related damage mechanisms, and Section 6.7.2.3 (SNL 2008b) describes the potential for waste package penetration by a drilling event. Implementation and the process for estimating the mean annual dose for the Human Intrusion Scenario is discussed in Section 6.7.3 (SNL 2008b). The requirement at 10 CFR 63.322(f), that only radionuclides transported to the saturated zone (SZ) need be considered, precludes consideration of exposure of the public, drillers, or other human intruders to radionuclides in cuttings, circulated materials, or tailings. The supplementary information in the preamble to 10 CFR Part 63 (p. 55761, Supplementary Information, 3.10 Human Intrusion Standard) is clear regarding the intent of the NRC on this point: Human intrusion has the potential for releasing particulate HLW to the surface with drill cuttings or providing a fast pathway for radionuclides to be transported to the SZ by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the SZ). NAS (The National Academy of Science) concluded, and the Commission agrees, that analysis of the risk to the public or the intruders (i.e., drilling crew) from radioactive drill cuttings left unattended at the surface for subsequent dispersal into the biosphere would not fulfill the purpose of the human intrusion calculation because it would not show how well a particular repository site and design would protect the public at large. Rather, an analysis of the hazard of particulate HLW left on the surface would be dominated by assumptions subject to significant speculation and uncertainty regardless of the particular site or design under evaluation. Additionally, the release to the surface represents a one-time release with no long-term effect on the repository barriers. Therefore, consideration of the exposure of intruders to radioactive waste is specifically excluded. Exposure as a consequence of human intrusion is limited to the transport of radionuclides by water flowing through a borehole that intrudes through a waste package, which is sufficiently degraded that it goes undetected by the drill operators, directly into the saturated zone.

Table 2.2-6. Human Intrusion—Related Features, Events, and Processes Included in the Performance Assessment to Demonstrate Compliance with Proposed 10 CFR 63.321 (Continued)

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
1.4.02.02.0A Inadvertent Human Intrusion (Continued)		In summary, inadvertent human intrusion is included in the demonstration of compliance with the individual protection standard for human intrusion (proposed 10 CFR 63.321), but does not require consideration within the demonstration of compliance with the individual protection standard after permanent closure (proposed 10 CFR 63.311) or within the demonstration of compliance with the groundwater protection standards (10 CFR 63.331). The assessment of inadvertent human intrusion is based on an evaluation of the dose resulting from a stylized scenario, which is discussed in included FEPs 1.4.04.00.0A, Drilling activities—human intrusion, and 1.4.04.01.0A, Effects of drilling intrusion.
1.4.04.00.0A Drilling Activities (Human Intrusion)	This FEP addresses any type of drilling activity in the repository environment. These activities may be taken with or without awareness of the presence of the repository and with or without consent of the repository licensee. Drilling activities may be associated with natural resource exploration (water, oil and gas, minerals, geothermal energy), waste disposal (liquid), fluid storage (hydrocarbon, gas), or reopening existing boreholes.	An assessment of human intrusion is required as part of the Yucca Mountain repository license application to demonstrate compliance with the stylized human intrusion scenario based on exploratory drilling for groundwater in proposed 10 CFR 63.321. The assessment of human intrusion is discussed in FEP 1.4.02.02.0A, Inadvertent human intrusion. Compliance with the human intrusion standard involves evaluation of the dose resulting from a stylized inadvertent human intrusion analysis. Other drilling activities associated with natural resource exploration (oil and gas, minerals, geothermal energy), waste disposal (liquid), fluid storage (hydrocarbon, gas), or reopening existing boreholes, are excluded by regulation. The stylized human intrusion scenario is implemented to demonstrate that the repository design will exhibit a measure of resilience against a typical human intrusion scenario. The scenario is not intended to represent all forms of human intrusion that could affect the repository. The scope of the stylized scenario is set out at 10 CFR 63.322, which requires that the analysis must assume the intrusion is the result of exploratory drilling for groundwater. Specifically, according to 10 CFR 63.322(a) it should be assumed that: There is a single human intrusion as a result of exploratory drilling for ground water and according to 10 CFR 63.322(c) it should be assumed that: The drillers use the common techniques and practices that are currently employed in exploratory drilling for ground water in the region surrounding Yucca Mountain. In summary, drilling activities (human intrusion) are included in the demonstration of compliance with the individual protection standard for human intrusion (proposed 10 CFR 63.321), but do not require consideration within the demonstration of compliance with the individual protection standard after permanent closure (proposed 10 CFR 63.311) or within the demonstration of compliance with the groundwater protection standards (10 CFR 63.331). The analysis conducted to demonstrate compliance with the individual protection standard for human intrusion is discussed in detail in included FEP 1.4.02.02.0A, Inadvertent human intrusion.

Table 2.2-6. Human Intrusion—Related Features, Events, and Processes Included in the Performance Assessment to Demonstrate Compliance with Proposed 10 CFR 63.321 (Continued)

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
1.4.04.01.0A Effects of Drilling Intrusion	Drilling activities that intrude into the repository may create new release pathways to the biosphere and alter existing pathways. Possible effects of a drilling intrusion include interaction with waste packages, increased saturation in the repository leading to enhanced radionuclide transport to the SZ, changes to groundwater and EBS chemistry, and waste brought to the surface.	An assessment of human intrusion is required as part of the Yucca Mountain repository license application. The effects of drilling intrusion are included in the demonstration of compliance with the individual protection standard for human intrusion (proposed 10 CFR 63.321), but do not require consideration within the demonstration of compliance with the individual protection standard after permanent closure (proposed 10 CFR 63.311) or within the demonstration of compliance with the groundwater protection standards (10 CFR 63.331). The analysis conducted to demonstrate compliance with the individual protection standard for human intrusion is discussed in detail in included FEP 1.4.02.02.0A, Inadvertent human intrusion. Compliance with the human intrusion standard involves evaluation of the dose resulting from a stylized inadvertent human intrusion scenario. The stylized human intrusion scenario is implemented to demonstrate that the repository design will exhibit a measure of resilience against a typical human intrusion scenario. The scenario is not intended to represent all forms of human intrusion that could affect the repository. The scope of the stylized scenario is set out at 10 CFR 63.322, which requires that the analysis must assume the intrusion is the result of exploratory drilling for groundwater, as discussed in FEP 1.4.04.00.0A, Drilling activities (human intrusion). 10 CFR 63.322 also specifies how the effects of drilling intrusion should be evaluated. In particular, according to 10 CFR 63.322 it should be assumed that: (b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository. and that: (d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole; (e) No particulate waste material falls into the borehole; (f) The exposure scenario includes only those radionuclides transported to the saturated zone by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the saturated zone); and (g) No releases are included which are caused by unlikely natural processes and events. As part of the evaluation of the effects of drilling intrusion to demonstrate compliance with the human intrusion standard at proposed 10 CFR 63.321(a) the NRC specifies that: DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers.

Table 2.2-6. Human Intrusion—Related Features, Events, and Processes Included in the Performance Assessment to Demonstrate Compliance with Proposed 10 CFR 63.321 (Continued)

FEP Number and Name	FEP Description	Summary of Technical Basis/Approach for FEP Inclusion
1.4.04.01.0A Effects of Drilling Intrusion (Continued)		As discussed in FEP 1.4.02.02.0A (Inadvertent Human Intrusion), inadvertent human intrusion is not considered to be possible while the drip shield and waste package remain intact. The rationale for this approach is given in *Total System Performance Assessment Model /Analysis for the License Application* (SNL 2008b, Section 6.7). Specifically, Section 6.7.2.3.4 (SNL 2008b) states: Selection of a bit for drilling involves knowledge of the characteristics of the rock. …there are significant differences between the tensile strengths and other material properties of the geologic units at Yucca Mountain and the materials for the drip shield and waste package. Because the materials used in the drip shield and waste packages have high tensile strengths, yield strengths and increased modulus of elasticity compared to the host rock properties, the tooth of a roller bit [typically used in drilling water wells due to their low cost and wide range of operational flexibility] cannot penetrate enough to cause sufficient strain for chipping to occur. Rather, if contact with the drip shield occurs, the rotation of the bit would result in a tearing or shearing action with associated and recognizable high torque values. Consequently, the ductility of the metals makes them nearly impenetrable by techniques used in drilling rock. Boring in metals typically utilizes a milling technique. The downhole milling tools needed to penetrate the drip shield and waste package are not typically used in groundwater exploration, and use of such tools would be a clear indicator of recognition of penetration of some type of metallic, anthropogenic structure. Consequently, penetration of the drip shield or waste package without recognition by the driller prior to general corrosion failure of the engineered barriers is not feasible. General corrosion failure of the drip shields is not expected to occur prior to 230,000 years (SNL 2008b, Section 6.7.2.1). Based on this analysis, unrecognized human intrusion is modeled conservatively to not occur prior to 200,000 years. In conclusion, the effects of drilling intrusion are included in the TSPA for the stylized human intrusion scenario (proposed 10 CFR 63.321 and 10 CFR 63.322). However, the assessment of human intrusion does not form part of the TSPA analyses for individual protection (proposed 10 CFR 63.311) or groundwater protection (10 CFR 63.331). The human intrusion standard is discussed in detail in included FEP 1.4.02.02.0A (Inadvertent Human Intrusion).

Source: SNL 2008a.

Table 2.2-7. Summary of Included FEPs Mapped to Model Abstraction Sections of the SAR

Yucca Mountain FEP Matrix			Processes							Events			
			Hydrologic and Thermal-Hydrologic	Chemical and Thermal-Chemical	Mechanical and Thermal-Mechanical	Microbiological	Radiological	Characteristics	Transport	Igneous	Seismic	Early Failure	Human Intrusion
Repository Subsystem Physical Elements and Features		Topography and Surficial Soils	2.3.1					2.3.1					
		Unsaturated Zone Above	2.3.1 2.3.2 2.3.3					2.3.1 2.3.2 2.3.3					
	Engineered Structures/Systems/Components	Emplacement Drifts	2.3.5	2.3.5	2.3.4			2.3.5		2.3.11	2.3.4		
		Backfill/Seals	See Note										
		Drip Shield	2.3.5	2.3.6								2.3.6	2.4
		Waste Package		2.3.6	2.3.6	2.3.6		2.3.6			2.3.4	2.3.6	2.4
		Cladding			2.3.7								
		Waste Form		2.3.7	2.3.7			2.3.7	2.3.7		2.3.4		
		Pallet		2.3.4							2.3.4		
		Invert	2.3.7	2.3.7					2.3.7				
		Unsaturated Zone Below	2.3.8					2.3.8	2.3.8				
		Saturated Zone	2.3.9					2.3.9	2.3.9				
		Biosphere	2.3.10				2.3.10	2.3.10	2.3.10	2.3.10 2.3.11			
		System											2.4

NOTE: Subsections of Section 2.3 noted above indicate where each included FEP is presented. System FEPs apply to the entire repository system and are not specifically mapped to individual sections. As described in Section 1.3.6, note that repository backfill is limited to the openings that connect the emplacement areas to the surface, mainly the ramps and shafts, and not the emplacement drifts themselves.

Table 2.2-8. Summary of Criticality Probabilities Used for Screening the Criticality Event Class

Location	Nominal Case	Seismic	Rockfall	Igneous	Total
Intact In-Package	—	—	—	—	—
Degraded In-Package	2.1×10^{-7}	3.7×10^{-5}	—	—	3.7×10^{-5}
Near Field	—	—	—	—	—
Far Field	—	—	—	—	—
Naval SNF In-Package					7.1×10^{-6}
Total Probability of Criticality					4.4×10^{-5}

NOTE: The value for the naval SNF in-package is provided in Naval Nuclear Propulsion Program Technical Support Document, Section 2.2.1.4.1.

Source: SNL 2008e, Section 7 (Values presented were summed from source).

Table 2.2-9. Principal Isotopes for Commercial Spent Nuclear Fuel Burnup Credit

Isotopes				
^{95}Mo	^{145}Nd	^{151}Eu	^{236}U	^{241}Pu
^{99}Tc	^{147}Sm	^{153}Eu	^{238}U	^{242}Pu
^{101}Ru	^{149}Sm	^{155}Gd	^{237}Np	^{241}Am
^{103}Rh	^{150}Sm	^{233}U	^{238}Pu	^{242m}Am
^{109}Ag	^{151}Sm	^{234}U	^{239}Pu	^{243}Am
^{143}Nd	^{152}Sm	^{235}U	^{240}Pu	—

Source: YMP 2003, Table 3-1.

Table 2.2-10. Calculated Isotopic Compositions for PWR and BWR Commercial SNF and Selected Initial Enrichment and Burnup Combinations

Nuclide	PWR			BWR	
Enrichment (wt% ^{235}U)/ burnup (GWd/MTU)	3.0 / 30	4.0 / 40	5.0 / 50	4.0 / 15	5.0 / 15
^{16}O	4.69×10^{-2}	4.65×10^{-2}	4.62×10^{-2}	4.74×10^{-2}	4.74×10^{-2}
^{98}Mo	4.12×10^{-5}	5.46×10^{-5}	6.77×10^{-5}	2.13×10^{-5}	2.19×10^{-5}
^{99}Tc	4.19×10^{-5}	5.47×10^{-5}	6.71×10^{-5}	2.17×10^{-5}	2.20×10^{-5}
^{101}Ru	3.93×10^{-5}	5.18×10^{-5}	6.40×10^{-5}	1.95×10^{-5}	1.95×10^{-5}
^{103}Rh	2.53×10^{-5}	3.11×10^{-5}	3.62×10^{-5}	1.42×10^{-5}	1.37×10^{-5}
^{109}Ag	4.35×10^{-6}	5.38×10^{-6}	6.33×10^{-6}	1.57×10^{-6}	1.32×10^{-6}
^{143}Nd	3.05×10^{-5}	3.98×10^{-5}	4.89×10^{-5}	1.88×10^{-5}	1.93×10^{-5}
^{145}Nd	2.40×10^{-5}	3.14×10^{-5}	3.86×10^{-5}	1.28×10^{-5}	1.31×10^{-5}
^{147}Sm	7.33×10^{-6}	9.12×10^{-6}	1.08×10^{-5}	4.39×10^{-6}	4.61×10^{-6}
^{149}Sm	1.65×10^{-7}	1.90×10^{-7}	2.13×10^{-7}	5.62×10^{-7}	6.37×10^{-7}
^{150}Sm	1.04×10^{-5}	1.36×10^{-5}	1.67×10^{-5}	4.73×10^{-6}	4.55×10^{-6}
^{151}Sm	5.23×10^{-7}	6.84×10^{-7}	8.44×10^{-7}	1.03×10^{-6}	1.06×10^{-6}
^{152}Sm	4.45×10^{-6}	5.48×10^{-6}	6.41×10^{-6}	1.86×10^{-6}	1.79×10^{-6}
^{151}Eu	2.12×10^{-8}	2.79×10^{-8}	3.45×10^{-8}	4.34×10^{-8}	4.51×10^{-8}
^{153}Eu	3.97×10^{-6}	5.32×10^{-6}	6.60×10^{-6}	1.46×10^{-6}	1.35×10^{-6}
^{155}Gd	1.03×10^{-7}	1.44×10^{-7}	1.86×10^{-7}	4.96×10^{-8}	4.60×10^{-8}
^{233}U	6.45×10^{-11}	9.96×10^{-11}	1.36×10^{-10}	9.28×10^{-11}	1.11×10^{-10}
^{234}U	3.69×10^{-6}	4.80×10^{-6}	5.68×10^{-6}	6.18×10^{-6}	8.17×10^{-6}
^{235}U	2.22×10^{-4}	2.65×10^{-4}	3.03×10^{-4}	6.62×10^{-4}	8.72×10^{-4}
^{236}U	8.99×10^{-5}	1.26×10^{-4}	1.64×10^{-4}	8.01×10^{-5}	9.07×10^{-5}
^{238}U	2.26×10^{-2}	2.22×10^{-2}	2.19×10^{-2}	2.25×10^{-2}	2.23×10^{-2}
^{237}Np	1.05×10^{-5}	1.57×10^{-5}	2.13×10^{-5}	8.09×10^{-6}	7.95×10^{-6}
^{238}Pu	3.40×10^{-6}	6.00×10^{-6}	9.27×10^{-6}	1.37×10^{-6}	1.18×10^{-6}
^{239}Pu	1.76×10^{-4}	1.96×10^{-4}	2.13×10^{-4}	2.86×10^{-4}	2.68×10^{-4}
^{240}Pu	5.12×10^{-5}	5.95×10^{-5}	6.66×10^{-5}	2.81×10^{-5}	2.35×10^{-5}
^{241}Pu	2.61×10^{-5}	3.21×10^{-5}	3.73×10^{-5}	1.22×10^{-5}	9.69×10^{-6}
^{242}Pu	9.38×10^{-6}	1.26×10^{-5}	1.57×10^{-5}	1.00×10^{-6}	6.86×10^{-7}

Table 2.2-10. Calculated Isotopic Compositions for PWR and BWR Commercial SNF and Selected Initial Enrichment and Burnup Combinations (Continued)

Nuclide	PWR			BWR	
Enrichment (wt% ^{235}U)/ burnup (GWd/MTU)	**3.0 / 30**	**4.0 / 40**	**5.0 / 50**	**4.0 / 15**	**5.0 / 15**
^{241}Am	8.17×10^{-6}	1.04×10^{-5}	1.24×10^{-5}	3.71×10^{-6}	2.95×10^{-6}
^{242m}Am	2.21×10^{-8}	3.66×10^{-8}	5.34×10^{-8}	8.40×10^{-9}	6.08×10^{-9}
^{243}Am	1.99×10^{-6}	3.17×10^{-6}	4.44×10^{-6}	1.45×10^{-7}	8.72×10^{-8}

Source: BSC 2003a; Wimmer 2004.

Table 2.2-11. Listing of Critical Limits

Waste Form	Representative fuel type	Trend Parameter	Critical Limit (Range of Applicability)
CSNF	PWR	None	0.9905 (0.0977 ≤ *EALF* ≤ 0.3882 eV) Fresh Fuel[a] – 0.0249 = 0.9656
		None	0.9778 (0.0684 ≤ *EALF* ≤ 1.0410 eV) Burned Fuel[a] – 0.0249 = 0.9529
	BWR	None	0.9905 (0.0977 ≤ *EALF* ≤ 0.3882 eV) Fresh Fuel[a] – 0.0249 = 0.9656
		None	0.9778 (0.0421 ≤ *EALF* ≤ 0.9679 eV) Burned Fuel[a] – 0.0249 = 0.9529
DOE1	FFTF	None	0.9786
DOE2	TRIGA	None	0.9796
DOE3	N Reactor	AENCF	0.0765 (AENCF) + 0.9434 (0 < AENCF < 0.175 MeV) 0.9568 (AENCF > 0.175 MeV)
DOE4	Shippingport PWR	AENCF	0.969 (0 < AENCF < 0.0278) –0.2336(AENCF) + 0.9755 (0.0278 < AENCF < 0.0922 MeV)
DOE5	Shippingport LWBR	None	0.9748
DOE6	Fort St. Vrain	AENCF	0.9608 (0 < AENCF < 0.4625 MeV) –0.0183(AENCF) + 0.9687 (0.4625 < AENCF < 0.8015 MeV)
DOE7	ATR	None	0.93[b]
DOE8	Enrico Fermi	None	0.9659
DOE9	TMI II	None	0.97[c]

NOTE: [a]Radulescu, Mueller et al. 2007, Table 20.
[b]BSC 2004b, p. 39.
[c]BSC 2004a, Section 6.
The critical limits identified from sources [b] and [c] are interim limits that have not been rigorously established, but will be confirmed prior to waste acceptance as identified in Table 5.10-3. See Table 2.2-12 for how the DOE1, DOE2, … DOE9 waste forms correlate to the criticality groups identified in Section 1.5.1.
AENCF = average energy of a neutron causing fission; ATR = advanced test reactor; BWR = boiling water reactor; EALF = energy corresponding to the average neutron lethargy causing fission; FFTF = fast flux test facility; LWBR = light water breeder reactor; TMI = Three Mile Island; TRIGA = Training, Research, Isotopes, General Atomic.

Source: BSC 2004d, Table 5, unless otherwise noted.

Table 2.2-12. Breakdown of Waste Package Variants

Waste Package Sequence	Waste Package Variant	Number of Waste Packages[a]	Fraction of Waste Packages	Number of Waste Packages	Fraction of Waste Packages	Number of Waste Packages	Fraction of Waste Packages
1	21-PWR TAD[b]	4,402	0.3942	4,568	0.4091	7,483	0.670
2	12-PWR Long TAD[c]	166	0.0149				
3	44-BWR TAD[d]	2,915	0.2610	2,915	0.2610		
4	NNPP SNF-Long[e]	310	0.0278	400	0.0358	400	0.036
5	NNPP SNF-Short[e]	90	0.0081				
6	DOE1-Long[f,g]	128	0.0115	143	0.0128	3,284	0.294
7	DOE1-Short[f,h]	15	0.0013				
8	DOE2-Short[i,h]	89	0.0080	89	0.0080		
9	DOE3-Long[j,g]	2	0.0002	17	0.0015		
10	DOE3-Short[j,h]	15	0.0013				
11	DOE3-MCO[j,k]	201	0.0180	201	0.0180		
12	DOE4-Long[l,g]	70	0.0063	733	0.0656		
13	DOE4-Short[l,h]	663	0.0594				
14	DOE5-Long[m,g]	40	0.0036	53	0.0047		
15	DOE5-Short[m,h]	13	0.0012				
16	DOE6-Long[n,g]	570	0.0510	572	0.0512		
17	DOE6-Short[n,h]	2	0.0002				
18	DOE7-Long[o,g]	236	0.0211	991	0.0887		
19	DOE7-Short[o,h]	755	0.0676				
20	DOE8-Long[p,g]	8	0.0007	18	0.0016		
21	DOE8-Short[p,h]	10	0.0009				
22	DOE9-Long[q,g]	420	0.0376	458	0.0410		
23	DOE9-Short[q,h]	38	0.0034				
24	DOE9-MCO[q,k]	9	0.0008	9	0.0008		

Table 2.2-12. Breakdown of Waste Package Variants (Continued)

Waste Package Sequence	Waste Package Variant	Number of Waste Packages[a]	Fraction of Waste Packages	Number of Waste Packages	Fraction of Waste Packages	Number of Waste Packages	Fraction of Waste Packages
Totals		11,167	1.00	11,167	1.00	11,167	1.00

NOTE: [a]Commercial and Naval Inventory; DOE-owned SNF Inventory labeled as Cx, x = 1 to 9 (Wheatley 2007, Point Estimate column {rounded up})
[b]21-PWR TAD–21-PWR TAD canister waste package variant.
[c]12-PWR Long TAD–12-PWR Long TAD canister waste package variant.
[d]44-BWR TAD–44-BWR canister waste package variant.
[e]NNPP–Naval Nuclear Propulsion Program.
[f]DOE1–Mixed Oxide (MOX) DOE SNF C2; representative fuel type–Fast Flux Test Facility (FFTF).
[g]Codisposal (CDSP) Long waste package variant.
[h]CDSP Short waste package variant.
[i]DOE2–Uranium-Zirconium Hydride (UZrHx) DOE SNF C7; representative fuel type–TRIGA.
[j]DOE3–Uranium Metal (U-Metal) DOE SNF C1; representative fuel type–N Reactor.
[k]Codisposal MCO waste package variant.
[l]DOE4–High-Enriched Uranium Oxide (HEU Oxide) DOE SNF C4; representative fuel type–Shippingport PWR.
[m]DOE5–Uranium/Thorium Oxide (U/Th Oxide) DOE SNF C5; representative fuel type–Shippingport LWBR.
[n]DOE6–Uranium/Thorium Carbide (U/Th Carbide) DOE SNF C6; representative fuel type–Fort St. Vrain
[o]DOE7–Aluminum Based DOE SNF C8; representative fuel type–Advanced Test Reactor (ATR).
[p]DOE8–Uranium-Zirconium/Uranium-Molybdenum (U-Zr/U-Mo) Alloy DOE SNF C3; representative fuel type–Enrico Fermi.
[q]DOE9–Low-Enriched Uranium Oxide (LEU Oxide) DOE SNF C9; representative fuel type–Three Mile Island II (TMI II).

Source: SNL 2008e, Table 4.1-2.

Table 2.2-13. Probability of Seismic Vibratory Ground Motion Events with Potential to Cause Damage to Codisposal Waste Packages

PGV Value (m/sec)	λ_1 **(Events/year)**	λ_2 **(Events/year)**	t_1 **(years)**	t_2 **(years)**	**Probability**
< 0.364	1.27×10^{-4}	NA	NA	NA	NA
0.364 – 0.4	9.30×10^{-5}	1.27×10^{-4}	10,000	0	2.87×10^{-1}
0.4 – 1.05	9.96×10^{-6}	9.30×10^{-5}	10,000	0	5.64×10^{-1}
1.05 – 2.44	4.52×10^{-7}	9.96×10^{-6}	10,000	0	9.07×10^{-2}
2.44 – 4.07	1.0×10^{-8}	4.52×10^{-7}	10,000	0	4.41×10^{-3}

NOTE: NA = not applicable.

Source: SNL 2008e, Table 6.4-6.

Table 2.2-14. Summary of External Criticality Results—Minimum Mass for $k_{eff} = 0.96$

Initiating Event	Waste Package Type	Calculated Accumulation or Mass Released from Waste Package	Mass of U or Pu (for FFTF) in kg required to achieve critical limit of k_{eff} = 0.96			
		Uranium mass, unless otherwise noted (kg)	Invert	Fractured Tuff	Lithophysae Array	Large Lithophysa
Seismic	DOE3 (N Reactor)	Not calc[a]	266,000	Inf[b]	Not calc	Not calc
	DOE9 (TMI II Fuel)	Not calc	350	Inf	Not calc	Not calc
	CSNF	90.3	126	Inf	Not calc[c]	Not calc
	DOE1 (FFTF) (Plutonium mass)	0	1.66	4.3	Not calc[d]	Not calc[d]
Igneous	DOE3 (N Reactor)	0.109	Inf	Inf	Not calc[e]	Inf
	DOE9 (TMI II Fuel)	30.7	538	Inf	Not calc[e]	Inf
	CSNF	74.8	159	Inf	1390	Inf
	DOE1 (FFTF) (Plutonium mass)	6.34×10^{-3}	1.66	4.3	4.0	2.2

NOTE: [a]"Not calc" means that this waste form was bounded by another waste from and or configuration. In most cases, this simply meant that, if commercial SNF waste was very subcritical, then TMI and N Reactor had to be also.
[b]"Inf" means that an infinite amount of fissile waste released in this model will not produce an arrangement that can reach the critical limit.
[c]Not calculated here because results of igneous show a value of 1,390 being required, and any calculation for the seismic initiating event may be slightly less than 1,390 kg but is much greater than the 90.3 kg that can accumulate.
[d]Not calculated here because it would be the same as for the igneous cases.
[e]Source identifies this as "Inf" but should be listed as "Not calc" as it is bounded by the commercial SNF results.

Source: SNL 2007a, Table 6.9-1[a].

Table 2.2-15. Mean Displacement Hazard at Nine Demonstration Sites

Site	Location	Mean Displacement (cm) Annual Exceedance Probability		
		1×10^{-6}	1×10^{-7}	1×10^{-8}
1	Bow Ridge Fault	73	220	590
2	Solitario Canyon Fault	180	490	1,300
3	Drill Hole Wash Fault	15	75	240
4	Ghost Dance Fault	15	69	210
5	Sundance Fault	6.1	40	140
6	Unnamed fault west of Dune Wash	13	71	210
7	About 100 m east of the Solitario Canyon Fault with the condition:			
7a	Small fault with 2 m cumulative displacement	2.1	18	73
7b	Shear with 0.10 m cumulative displacement	1.0	5.6	9.0
7c	Fracture	0.11	0.53	0.63
7d	Intact rock	—	—	—
8	Between Solitario Canyon and Ghost Dance Fault with the condition:			
8a	Small fault with 2 m cumulative displacement	2.0	18	78
8b	Shear with 0.10 m cumulative displacement	0.89	5.5	8.8
8c	Fracture	0.10	0.52	0.63
8d	Intact rock	—	—	—
9	Midway Valley	11	67	210

NOTE: Displacement values for a specific annual exceedance probability are determined from the logarithms of the data using linear interpolation.

Source: BSC 2004h, Figures 18 through 22.

Table 2.2-16. Summary of Predicted Mean Horizontal Ground Motion Hazard at Yucca Mountain

Annual Exceedance Probability	Spectral Response Frequency (Hz)				Peak Ground Velocity (m/s)
	100[a]	10	1	0.3	
5×10^{-4}	0.25 g	0.53 g	0.23 g	0.076 g	0.22
1×10^{-4}	0.53 g	1.2 g	0.47 g	0.17 g	0.48
1×10^{-5}	1.3 g	3.0 g	1.2 g	0.44 g	1.3
1×10^{-6}	2.9 g	4.4 g	2.6 g	1.1 g	3.0
1×10^{-7}	5.8 g	11 g	5.5 g	2.3 g	6.5

NOTE: [a]Peak ground acceleration.
Ground motion values are for the hypothetical reference rock outcrop defined for the PSHA (BSC 2004h, Section 6.3.3.1.1). They do not reflect site-response modeling (Section 2.3.4.3.2) that is required to obtain ground motions for the repository waste emplacement level. They also do not reflect reduction (conditioning) of the ground motion annual probabilities of exceedance to reflect constraints related to the geologic setting of Yucca Mountain (Section 2.3.4.3.3).
Ground motion values for a specific annual exceedance probability are determined from the logarithms of the data using linear interpolation.

Table 2.2-17. Summary of Local Fault Parameters from the Seismic Source Characterization for the Probabilistic Seismic Hazard Analysis

Fault	Probability of Activity	Maximum Magnitude	Slip Rate (mm/yr)	Recurrence Interval (ka)
Bare Mountain	1.0	5.8 to 7.5	0.005 to 0.25	20 to 200
Black Cone	0.8	5.0 to 7.0	0.001 to 0.005	—
Bow Ridge	0.4 to 1.0	5.2 to 7.0	0.002 to 0.007	40 to 350
Crater Flat fault system	1.0	5.3 to 7.0	0.001 to 0.003	—
Central Crater Flat	0.6	5.3 to 7.0	0.001 to 0.005	—
Southern Crater Flat	1.0	5.4 to 7.0	0.002 to 0.02	40 to 180
Northern Crater Flat	1.0	5.5 to 7.0	0.001 to 0.005	120 to 160
Dune Wash	0.1	4.9 to 7.2	0.0001 to 0.001	—
East Busted Butte	0.4	4.5 to 7.2	0.0005 to 0.003	—
East Lathrop Wells Cone	1.0	4.6 to 6.9	0.005 to 0.003	—
Fatigue Wash	1.0	5.5 to 7.3	0.002 to 0.02	50 to 250
Fatigue Wash-Windy Wash	1.0	5.6 to 7.2	0.005 to 0.024	—
Ghost Dance Fault Zone	0.05 to 0.1	4.5 to 7.0	0.0001 to 0.002	—
Iron Ridge	0.1 to 1.0	5.1 to 7.0	0.001 to 0.005	—
Iron Ridge-Solitario Canyon	1.0	5.5 to 7.2	0.005 to 0.024	—
Midway Valley	0.1	4.9 to 7.1	0.0001 to 0.001	—
Paintbrush Canyon	1.0	5.9 to 7.4	0.002 to 0.03	20 to 270
Paintbrush Canyon-Stagecoach Road	1.0	5.6 to 7.3	0.009 to 0.05	15 to 120
Paintbrush-Stagecoach-Bow Ridge	1.0	5.5 to 7.6	0.005 to 0.02	10 to75
Solitario Canyon	1.0	5.6 to 7.4	0.002 to 0.04	35 to 180
Stagecoach Road	1.0	5.3 to 7.1	0.01 to 0.07	5 to 75
Windy Wash	1.0	6.6 to 7.5	0.01 to 0.027	35 to 100
South Windy Wash	1.0	5.7 to 7.1	0.01 to 0.04	20 to 60
North Windy Wash	1.0	5.6 to 7.2	0.001 to 0.005	—

NOTE: Parameter ranges were developed from all teams reporting (i.e., one to six teams); all parameter ranges were provided as probability distributions. Recurrence intervals were not determined for some faults.

Source: BSC 2004j, Table 4-11.

Table 2.2-18. Published Estimates of the Probability of Intersection of the Repository at Yucca Mountain by a Volcanic Event

Reference	Intersection Probability (per Year)	Comment	Event Representation
Crowe, Johnson et al. 1982, pp. 184 to 185	3.3×10^{-10} to 4.7×10^{-8}	Range of alternative probability calculations	Point
Crowe, Perry, Valentine et al. 1993, p. 188	2.6×10^{-8}	Median value of probability distribution	Point
Connor and Hill 1995, p. 10121	1×10^{-8} to 5×10^{-8}	Range of three alternative models	Point
Crowe, Perry, Geissman et al. 1995, Table 7.22	1.8×10^{-8}	Median value of 22 alternative probability models	Point
Ho and Smith 1998, pp. 507 to 508	(1) 1.5×10^{-8}, (2) 1.09×10^{-8}, 2.83×10^{-8}, (3) 3.14×10^{-7}	Three alternative models; third model assumes a spatial intersection ratio (using a Bayesian prior) of 8/75 or 0.11, approximately 1 order of magnitude higher than other published estimates, because volcanic events are forced to occur within a small zone enclosing Yucca Mountain	Point
CRWMS M&O 1998b, Chapter 6, p. 6-84	2.5×10^{-8}	Sensitivity analysis that assumes all aeromagnetic anomalies in Amargosa Valley are Quaternary age	Point
Connor et al. 2000, p. 427	10^{-8} to 10^{-7}	Value of 10^{-7} assumes maximum event length of 20 km, regional recurrence rates of five events per million years, and that crustal density variations contribute to event location.	Line

Source: BSC 2004k, Table 6-5.

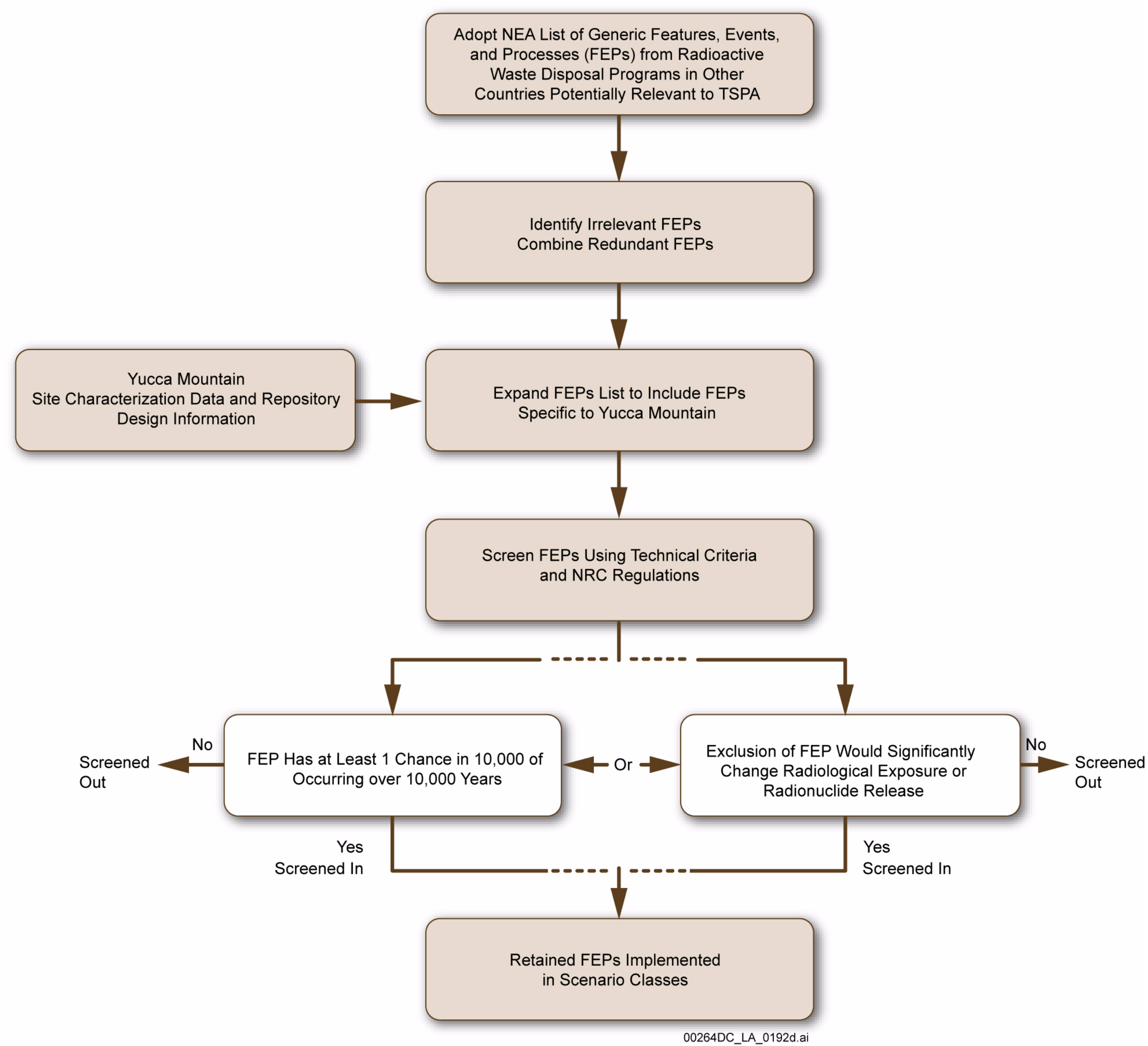

Figure 2.2-1. Features, Events, and Processes Screening Process

Source: SNL 2008c, Figure 6-1.

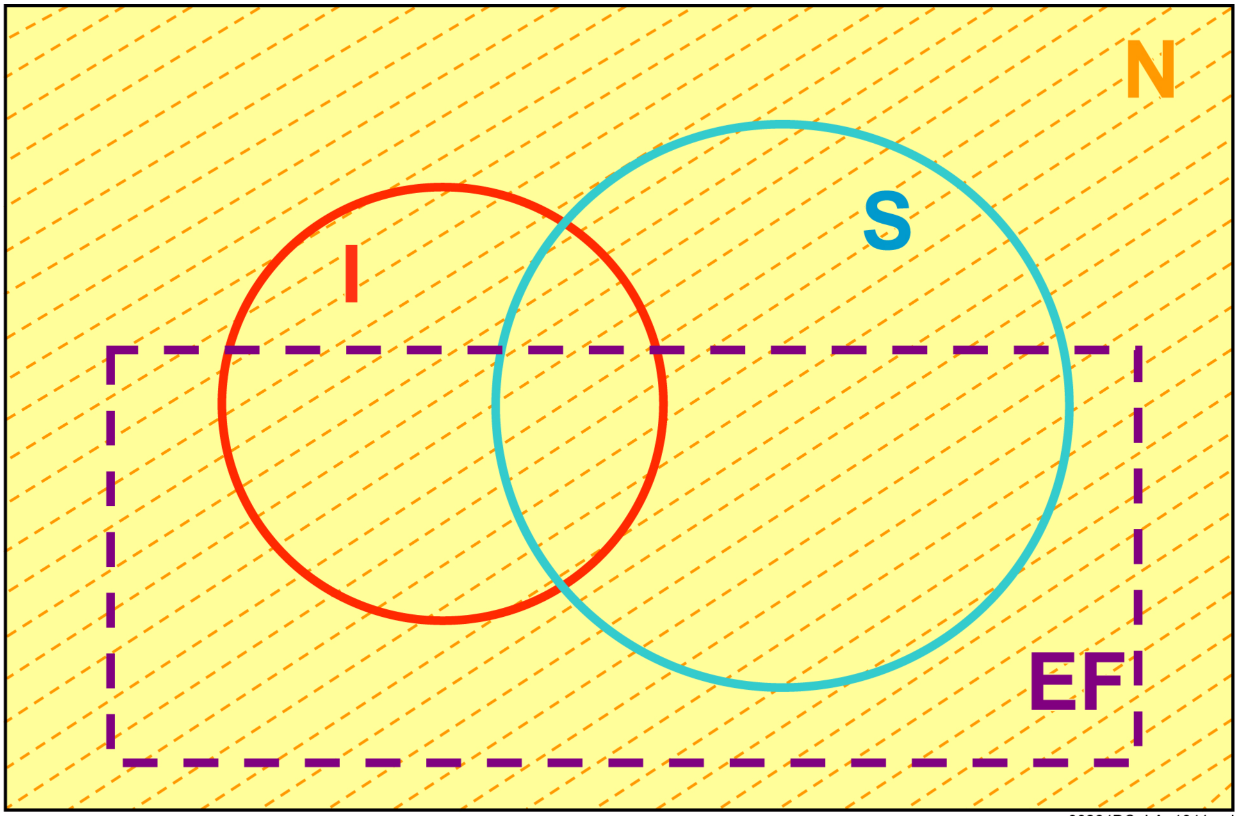

Figure 2.2-2. Venn Diagram Representing Sets of Futures Associated with Igneous, Seismic, and Early Failure Events

NOTE: The overlap of areas indicates that these futures are independent and not mutually exclusive. I = igneous; EF = early failure; N = nominal; S = seismic.

Source: SNL 2008c, Figure 6-2.

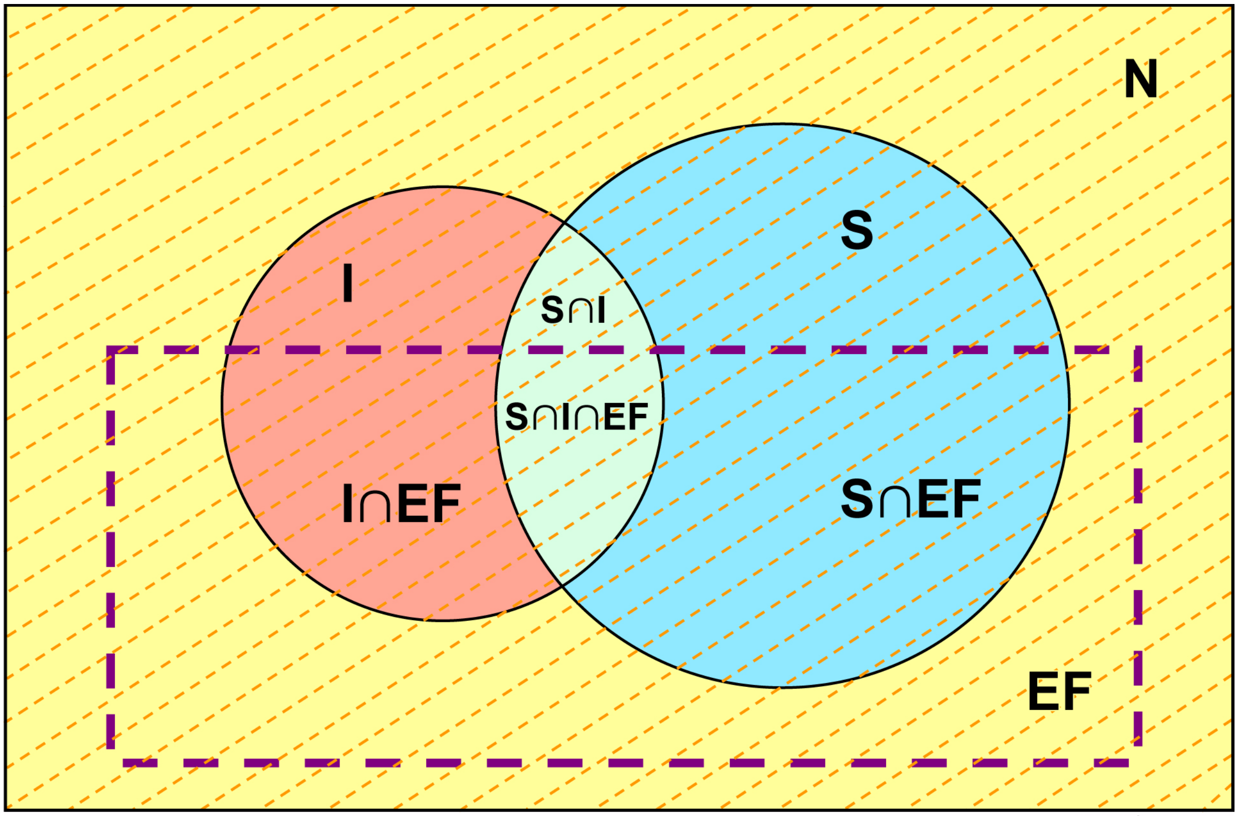

Figure 2.2-3. Venn Diagram Representing Sets of Futures Associated with Igneous, Seismic, and Early-Failure Events: Nominal, Seismic, Igneous, Early-Failure, Igneous/Seismic, Seismic/Early-Failure, Igneous/Early-Failure, and Igneous/Seismic/Early-Failure Scenario Sets

Source: SNL 2008c, Figure 6-3.

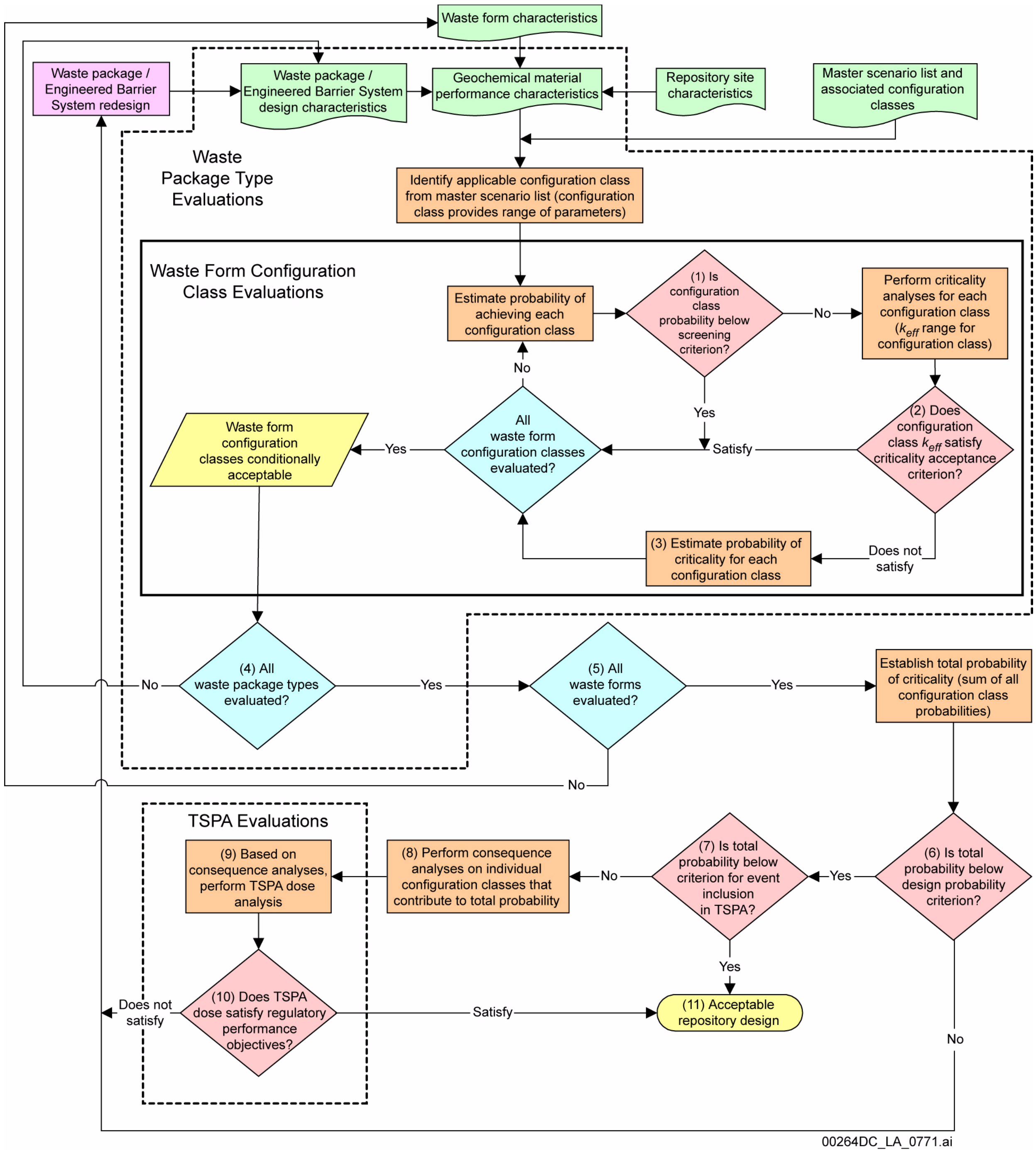

Figure 2.2-4. Disposal Criticality Analysis Methodology Approach

Source: YMP 2003, Figure 3-1.

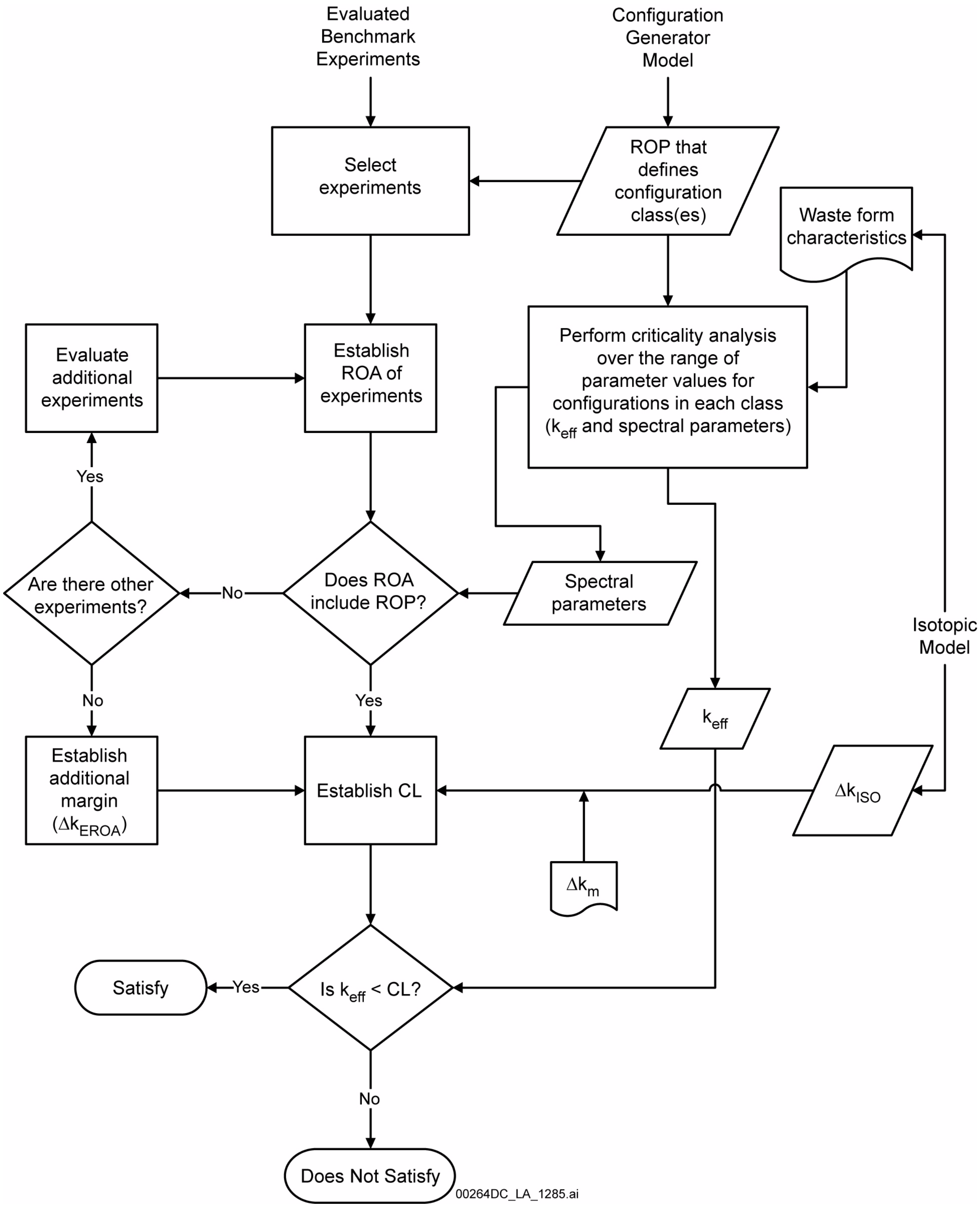

Figure 2.2-5. Criticality Model Overview

NOTE: CL = Critical Limit, EROA = Extension of the Range of Applicability, ROA = Range of Applicability, ROP = Range of Parameters.

Source: YMP 2003, Figure 3-4.

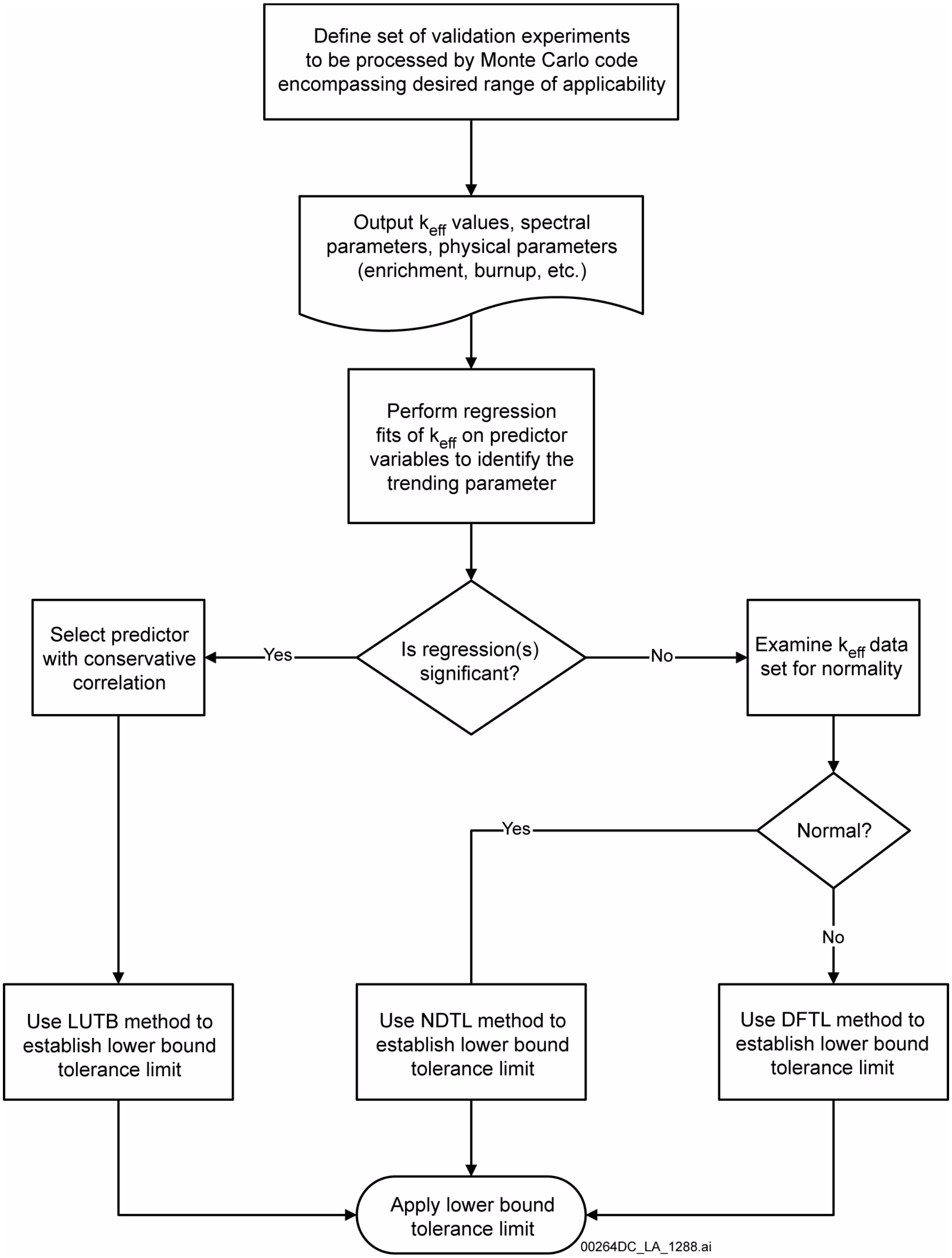

Figure 2.2-6. Process for Calculating Lower Bound Tolerance Limits

NOTE: LUTB = lower uniform tolerance band; NDTL = normal distribution tolerance limit; DFTL = distribution free tolerance limit.

Source: YMP 2003, Figure 3-6.

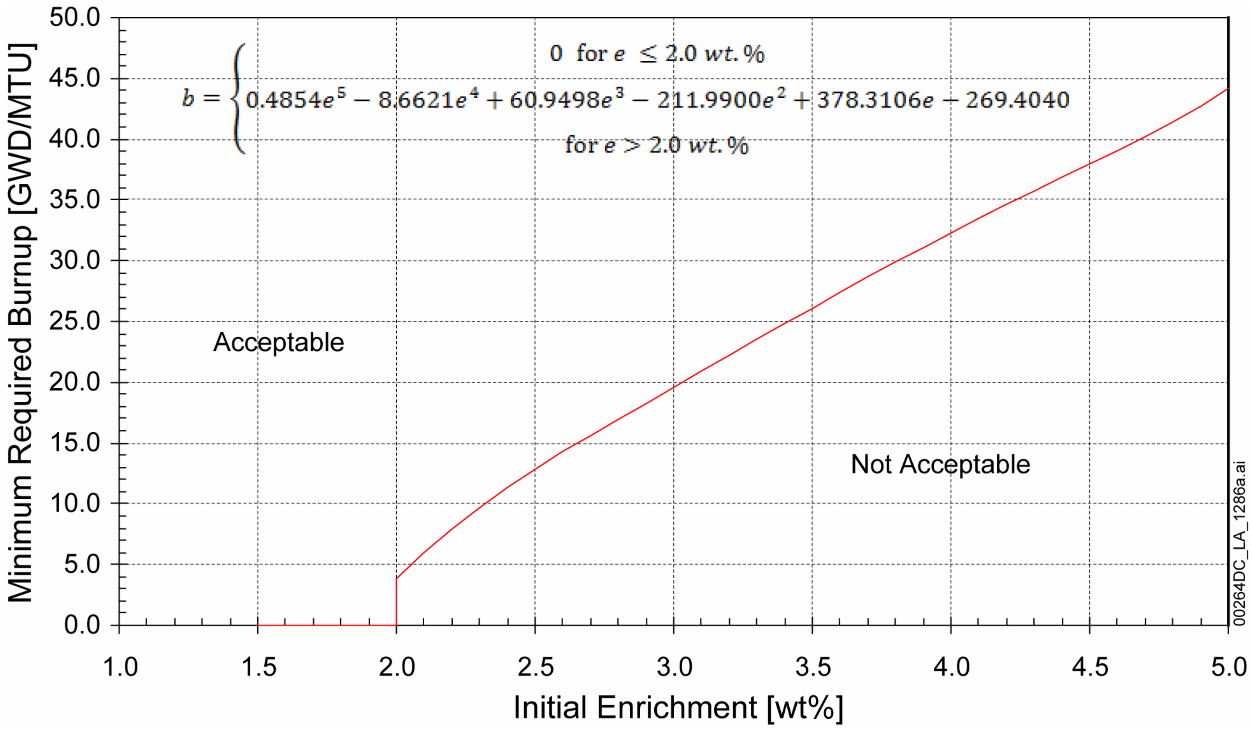

Figure 2.2-7. 21-PWR TAD Loading Curve

Source: SNL 2008d, Section 7.

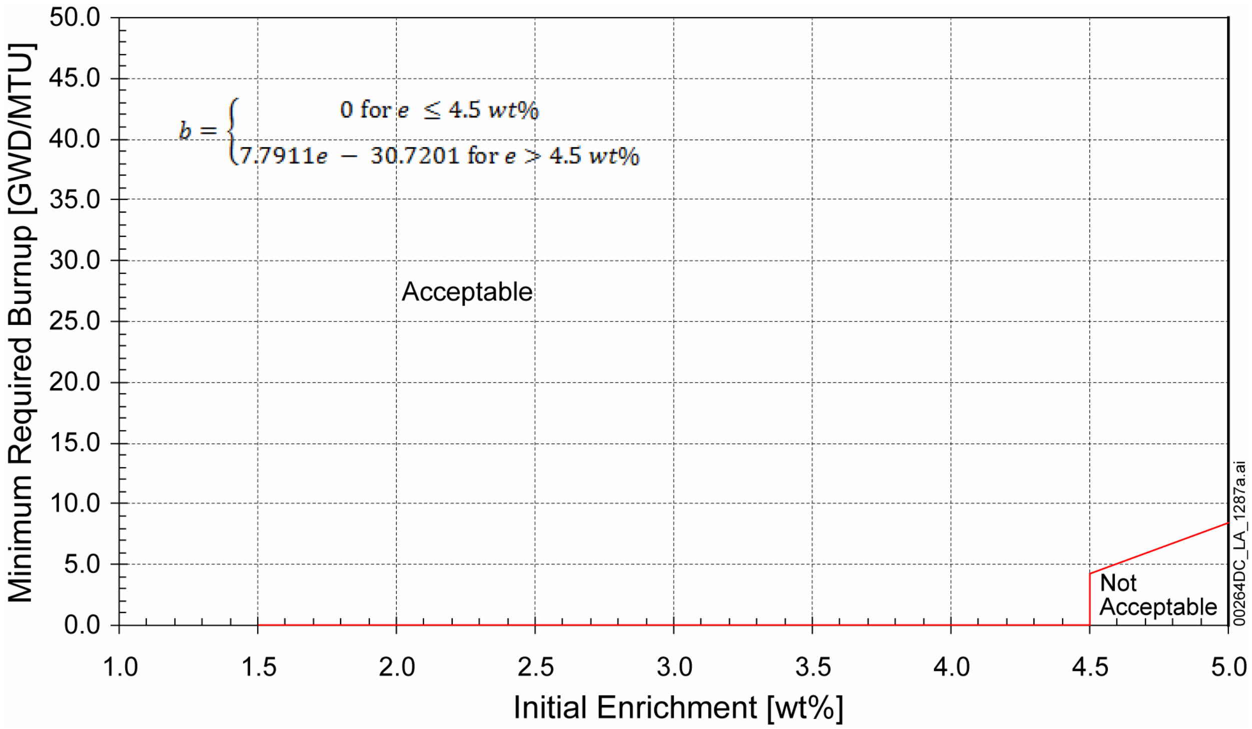

Figure 2.2-8. 44-BWR TAD Loading Curve

Source: SNL 2008d, Section 7.

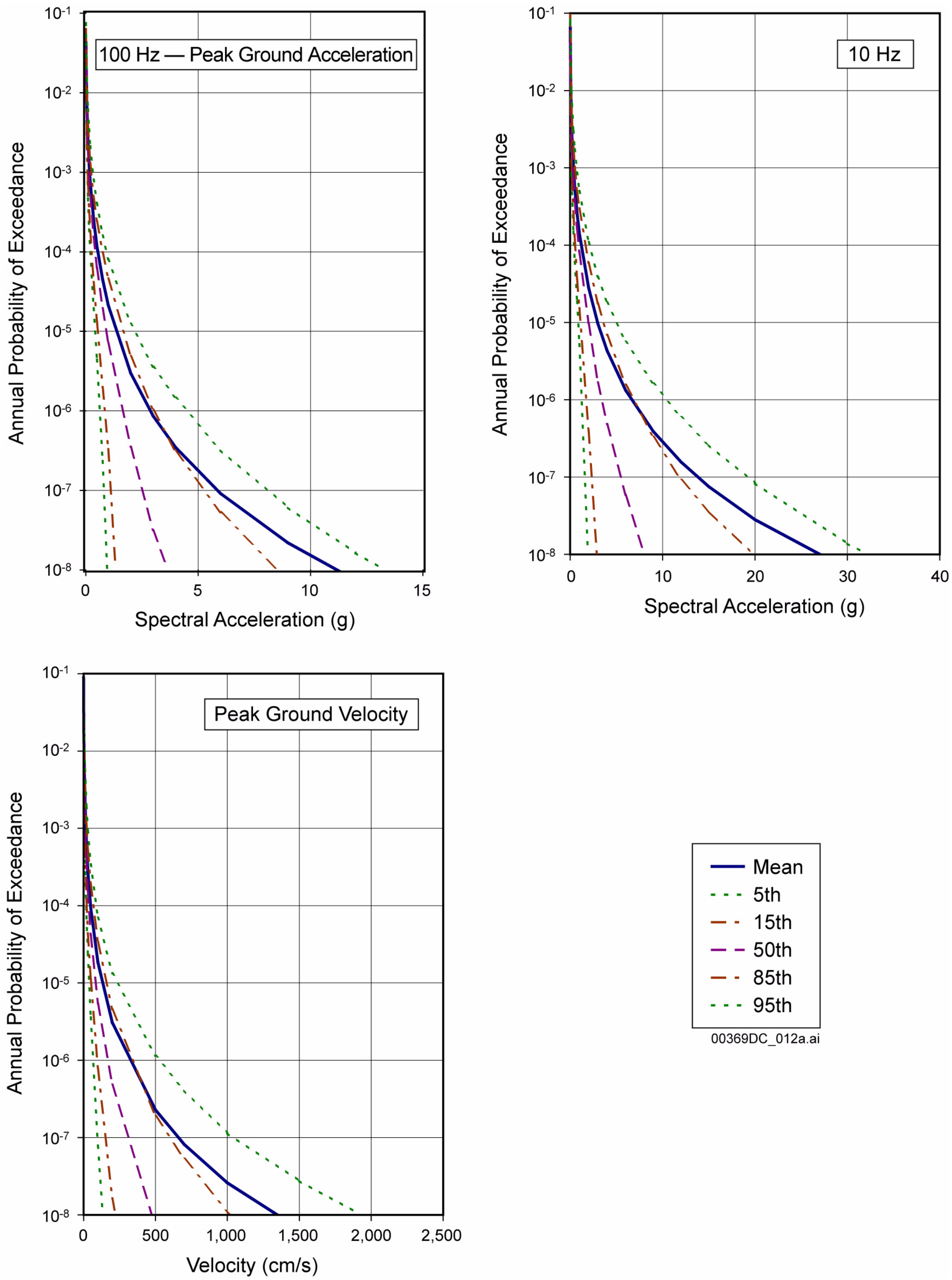

Figure 2.2-9. Summary Ground-Motion Hazard Curves for Yucca Mountain

NOTE: Ground motion values are for the hypothetical reference rock outcrop defined in the PSHA (BSC 2004h, Section 6.3.3.1.1). They do not reflect site-response modeling (Section 2.3.4.3.2) that is required to obtain ground motions for the repository waste emplacement level. They also do not reflect conditioning (reduction) of the ground motion annual probabilities of exceedance to reflect constraints related to the geologic setting of Yucca Mountain (Section 2.3.4.3.3).

Source: BSC 2004i, Figures 6.2-1, 6.2-2, and 6.2-4.

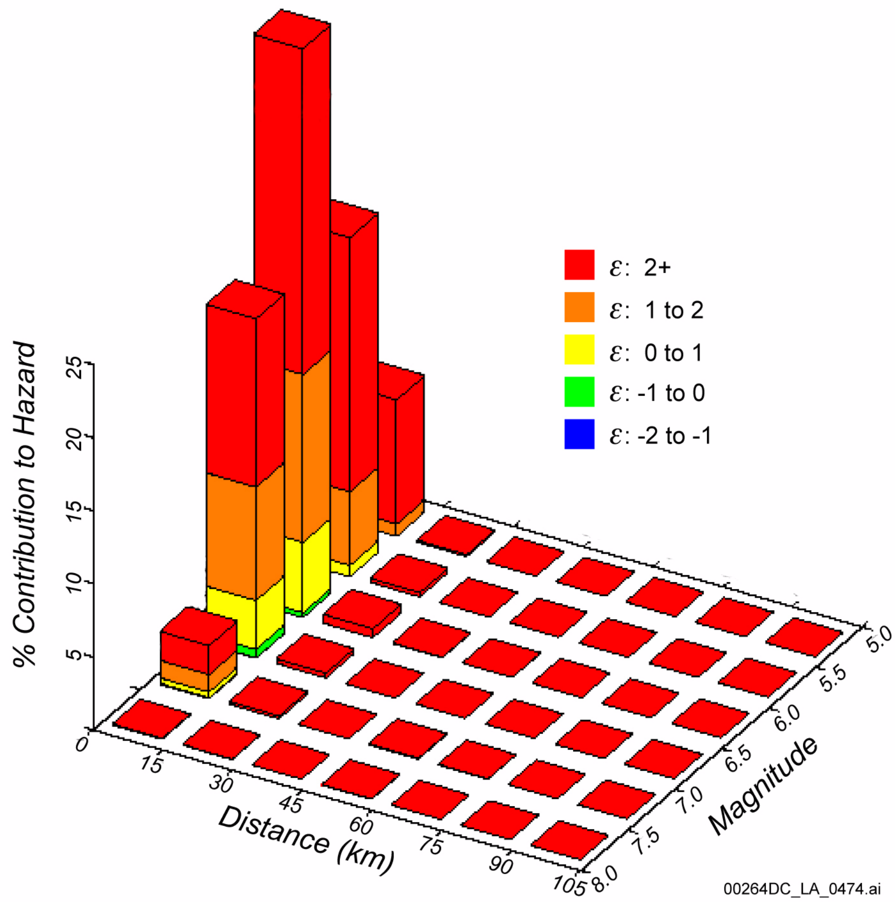

Figure 2.2-10. Contribution to Hazard by Magnitude (M_w), Distance, and Epsilon (ε) for the 5 to 10 Hz Horizontal Ground Motions, 10^{-6} Annual Exceedance Probability

NOTE: Deaggregation results shown on this figure are used in developing control motions for ground motion site-response modeling (Section 2.3.4.3.2.1).

Source: BSC 2004i, Figure 6.2-21.

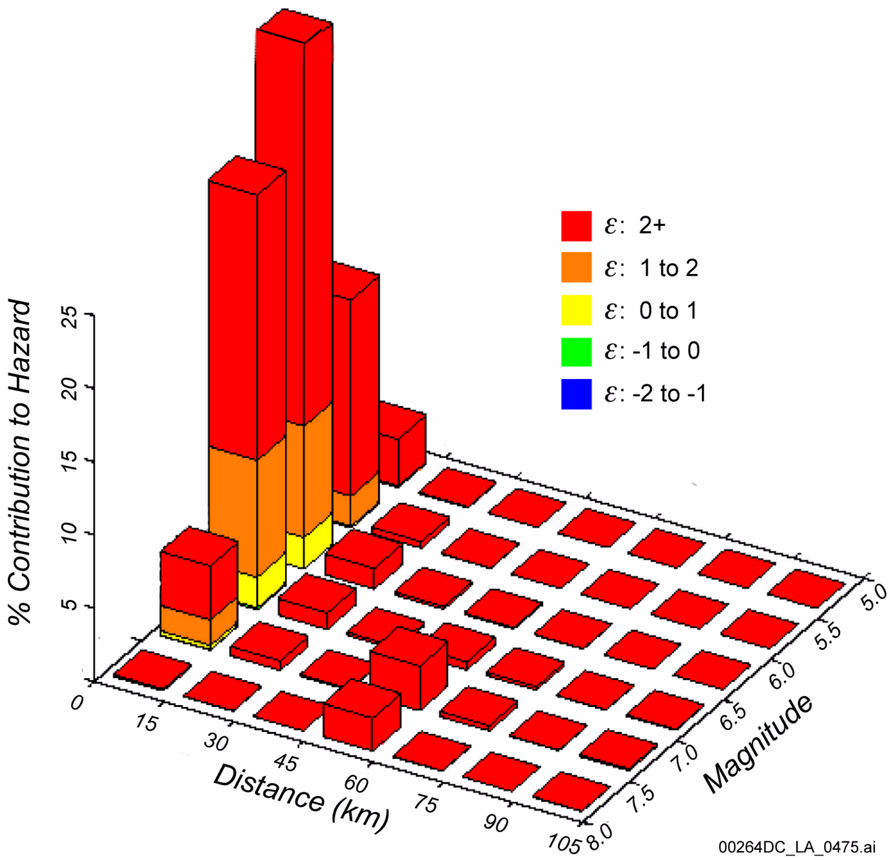

Figure 2.2-11. Contribution to Hazard by Magnitude (M_w), Distance, and Epsilon (ε) for the 1 to 2 Hz Horizontal Ground Motions, 10^{-6} Annual Exceedance Probability

NOTE: Deaggregation results shown on this figure are used in developing control motions for ground motion site-response modeling (Section 2.3.4.3.2.1).

Source: BSC 2004i, Figure 6.2-27.

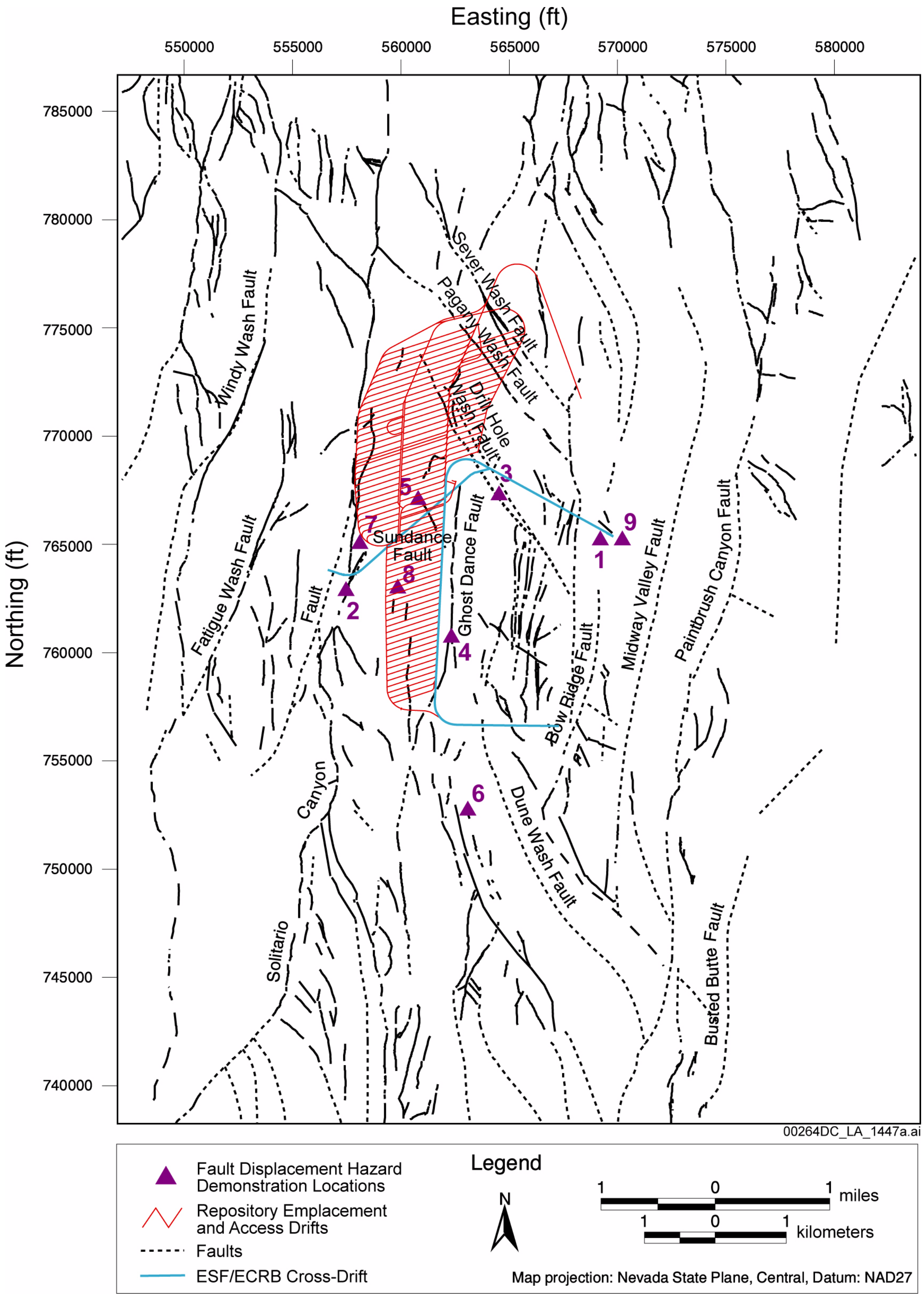

Figure 2.2-12. Locations for Demonstration of Fault Displacement Hazard Assessment

NOTE: See Table 2.2-15 for descriptions of demonstration locations.

Source: Modified from CRWMS M&O 1998a, Figure 4-9.

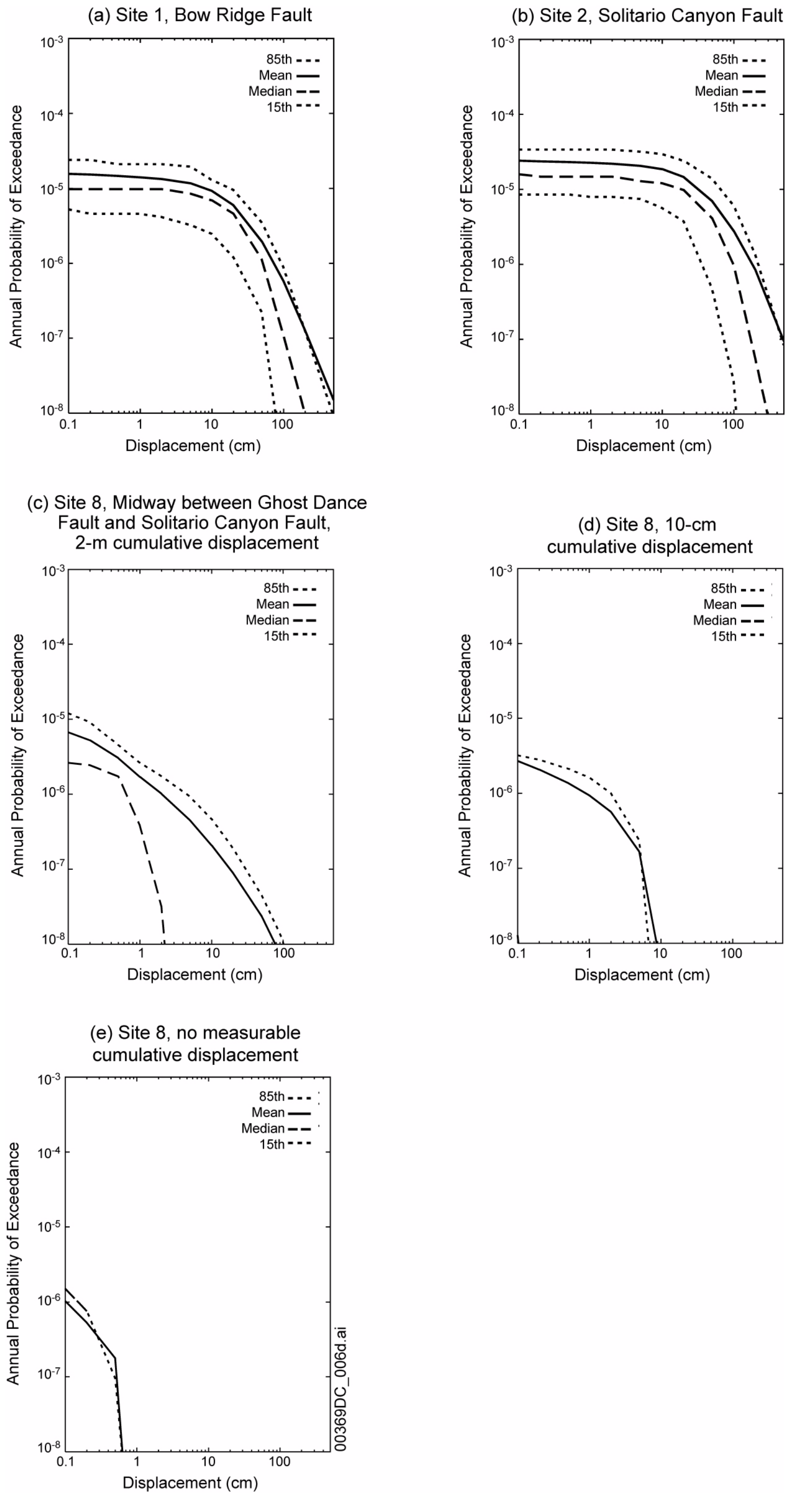

Figure 2.2-13. Example Summary Fault Displacement Hazard Curves for Yucca Mountain

NOTE: On (c) the 15th percentile curve has an annual probability of exceedance of less than 10^{-8} and is not shown. On (d) and (e) the median and 15th percentile curves have an annual probability of exceedance of less than 10^{-8} and are not shown.

Source: CRWMS M&O 1998a, Figures 8-2, 8-3, 8-11, 8-12, and 8-13.

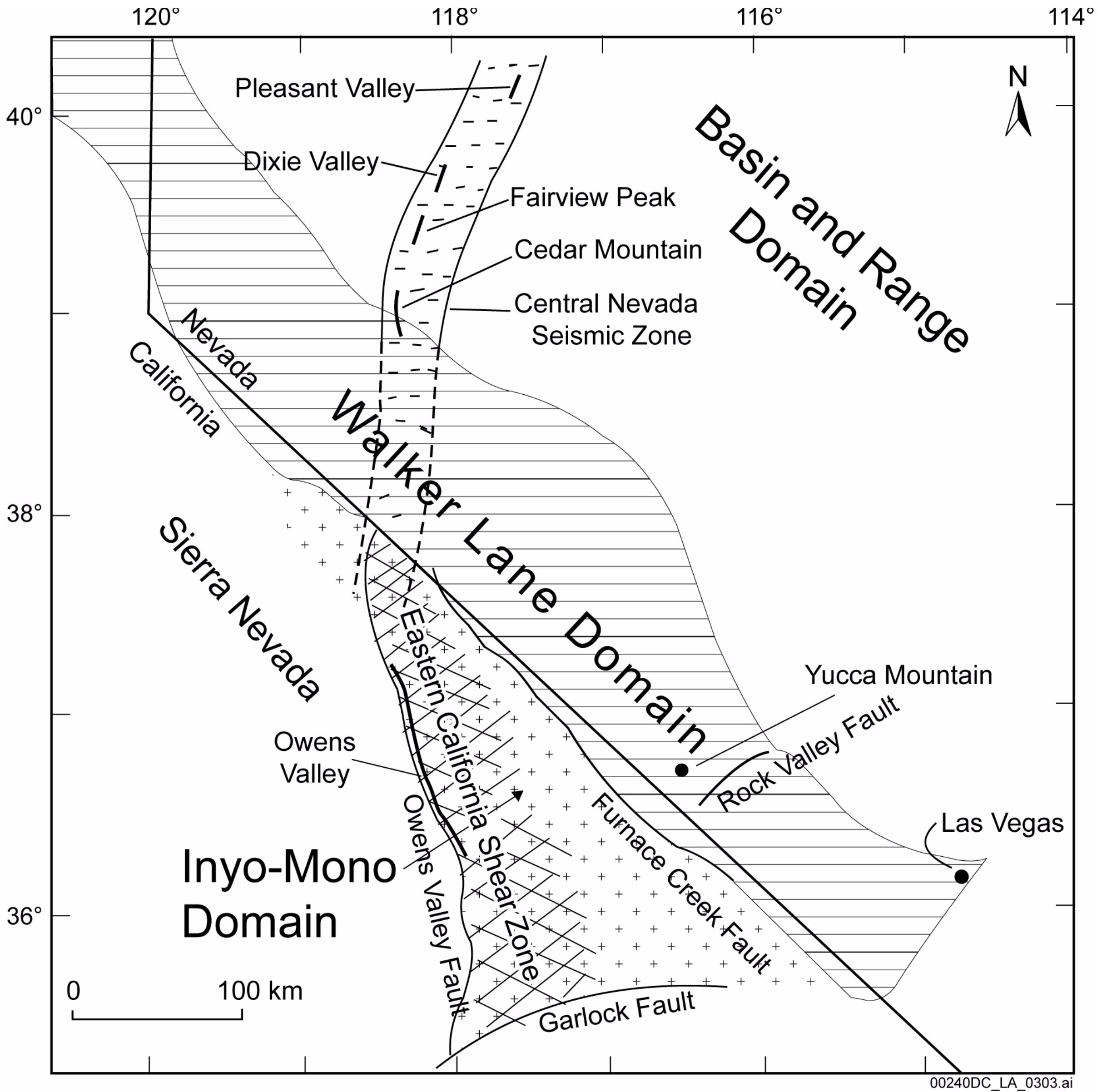

Figure 2.2-14. Regional Tectonic Domains for Yucca Mountain and Surrounding Environs, plus Zones of Historical Seismic Activity

Source: BSC 2004j, Figure 2-3.

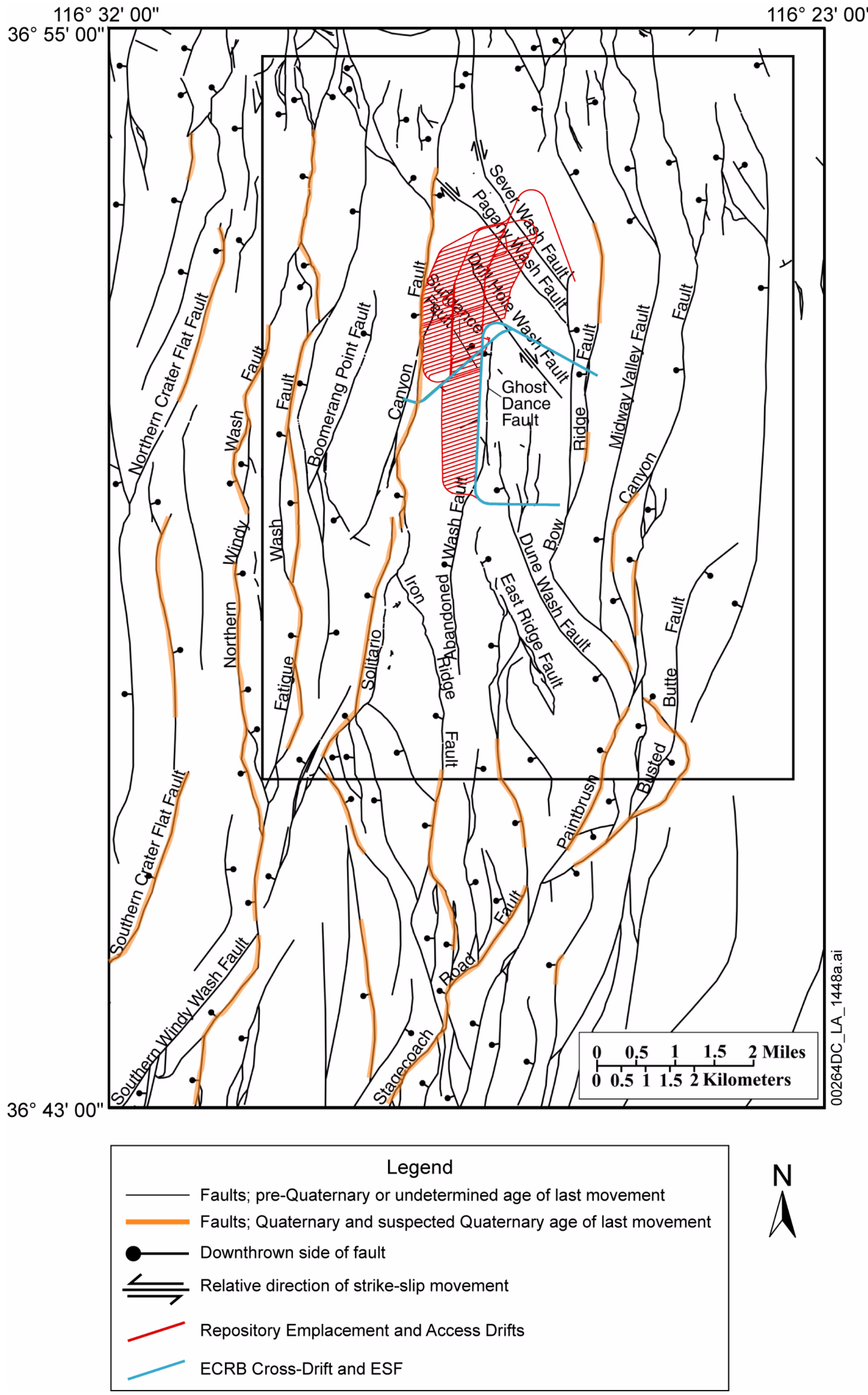

Figure 2.2-15. Distribution of Faults in the Yucca Mountain Site Area and Adjacent Areas South and West

NOTE: All faults are shown with solid lines, although many segments are concealed or inferred. Additional information is available in *Geologic Map of the Yucca Mountain Region, Nye County, Nevada* (Potter et al. 2002).

Source: BSC 2004j, Figure 3-20.

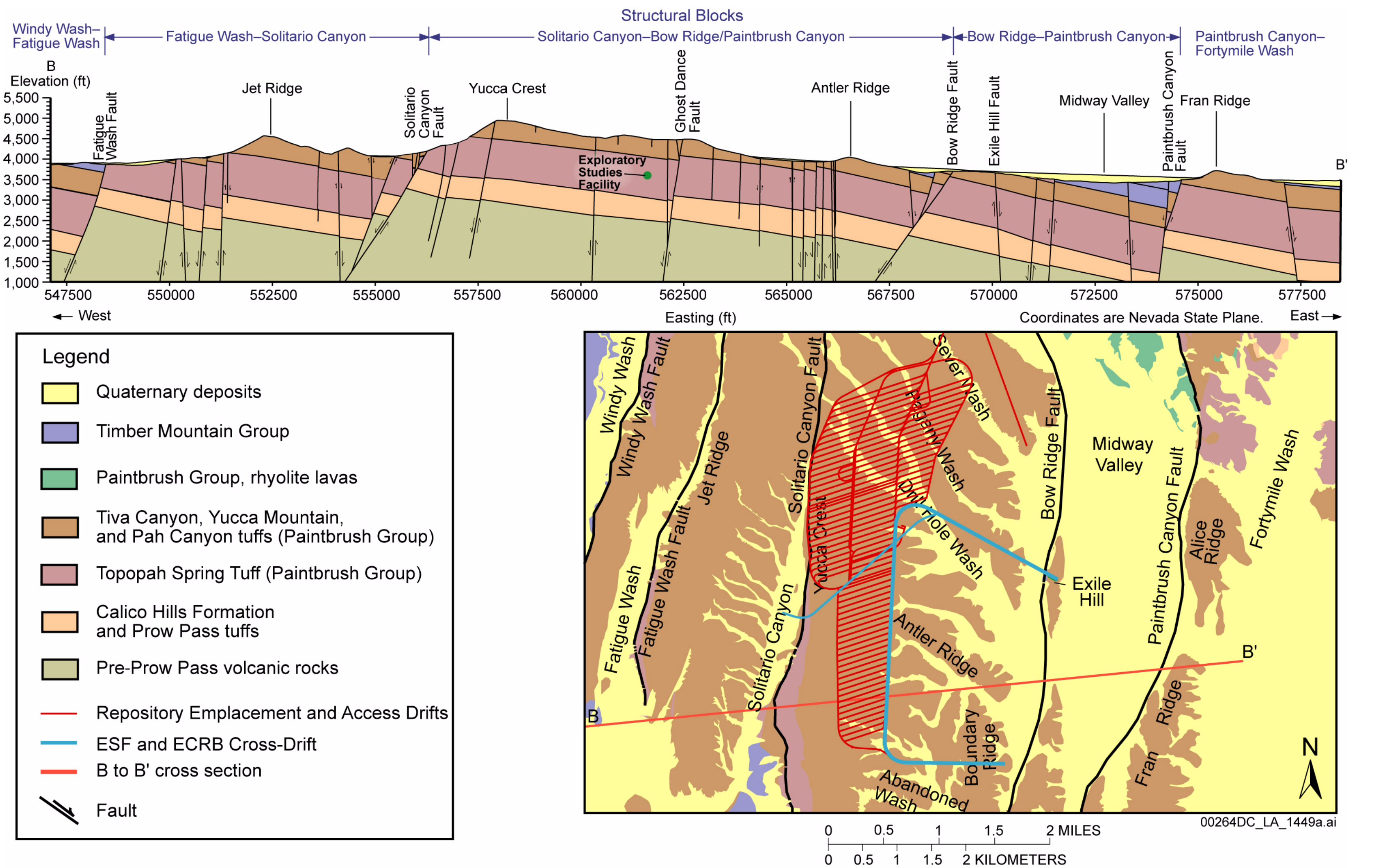

Figure 2.2-16. Approximate East–West Geologic Section across Yucca Mountain Site Area (top) along Line of Cross Section in Plan View (bottom)

NOTE: Location of intersection along line of section.

Source: Day et al. 1998, cross section B-B; Potter et al. 2002, plan view.

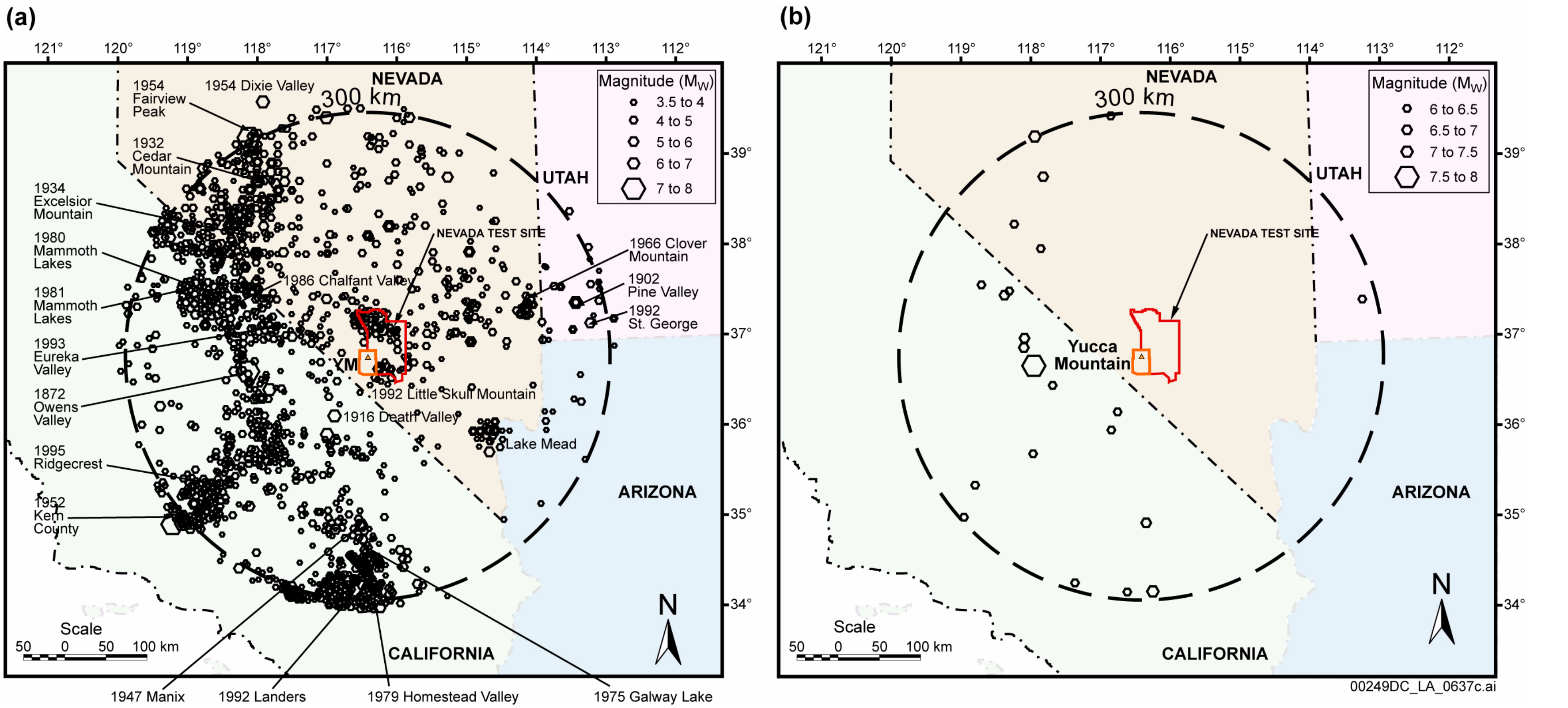

Figure 2.2-17. Historical Earthquake Epicenters within 300 km of Yucca Mountain

NOTE: (a) shows earthquakes of M_w greater than 3.5. (b) shows earthquakes of M_w greater than 6.0. Note change in magnitude scale. Earthquakes from 1868 to 1998 are shown. Coverage of older seismicity is sparse because of the absence or limited availability of seismographic coverage in the late 1800s and early 1900s. The cluster of earthquakes near the southern boundary of the Nevada Test Site represents the 1992 Little Skull Mountain earthquake and its numerous aftershocks. Many of the events in the northern part of the Nevada Test Site occurred in response to underground nuclear explosions. Significant earthquakes are labeled with year of occurrence. In (a), the Dixie Valley and Kern County earthquakes are greater than 300 km from Yucca Mountain but are shown because of their historical and seismological significance.

Source: BSC 2004j, Figure 4-18.

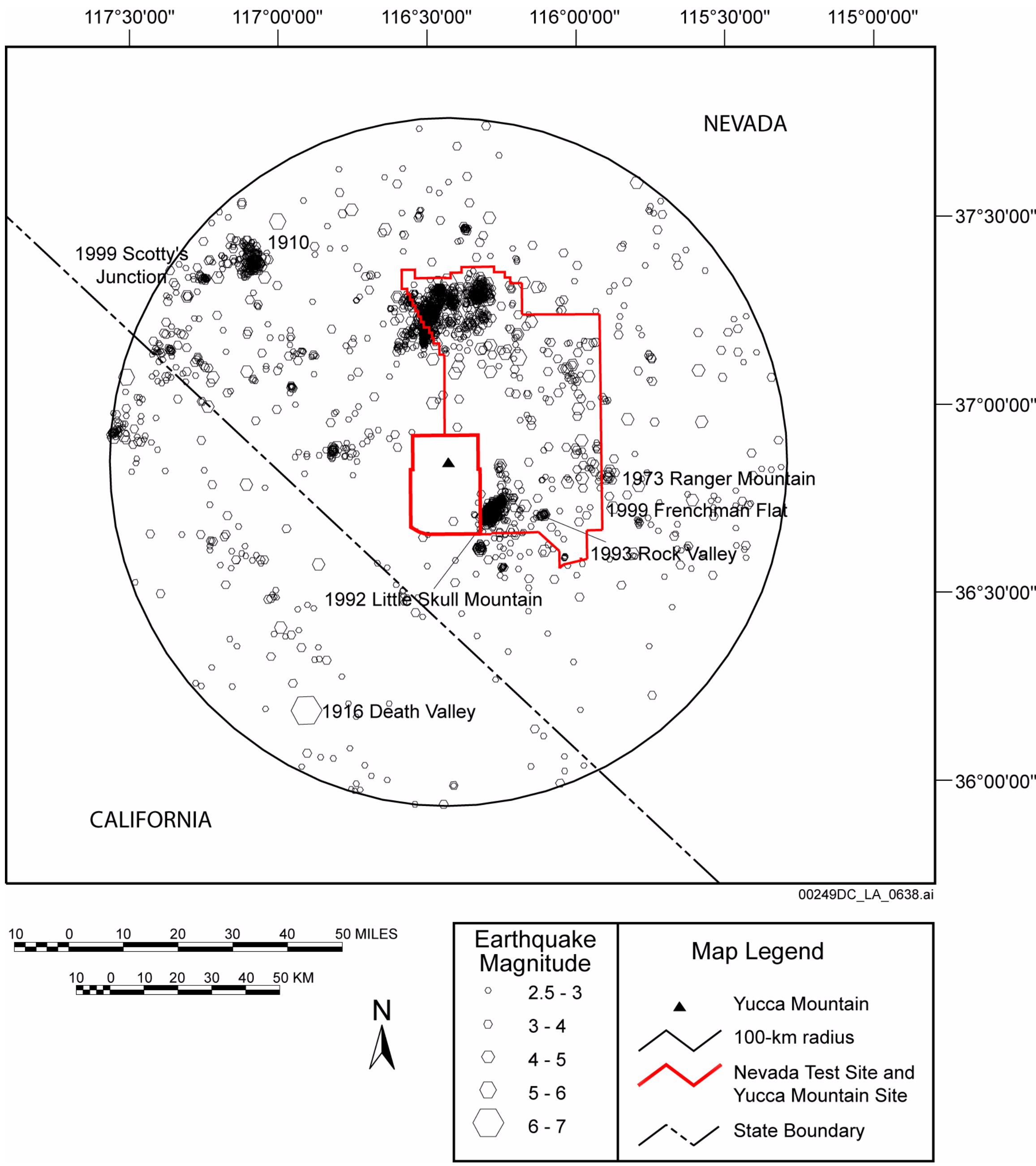

Figure 2.2-18. Historical Earthquake Epicenters within 100 km of Yucca Mountain

NOTE: Shown are earthquakes from 1904 to 1998. Earthquakes associated with the 1999 Scotty's Junction and 1999 Frenchman Flat sequences are also shown. Significant earthquakes or earthquake sequences are shown with years of occurrence. Activity in the northwestern corner of the Nevada Test Site is related to underground nuclear testing.

Source: BSC 2004j, Figure 4-19.

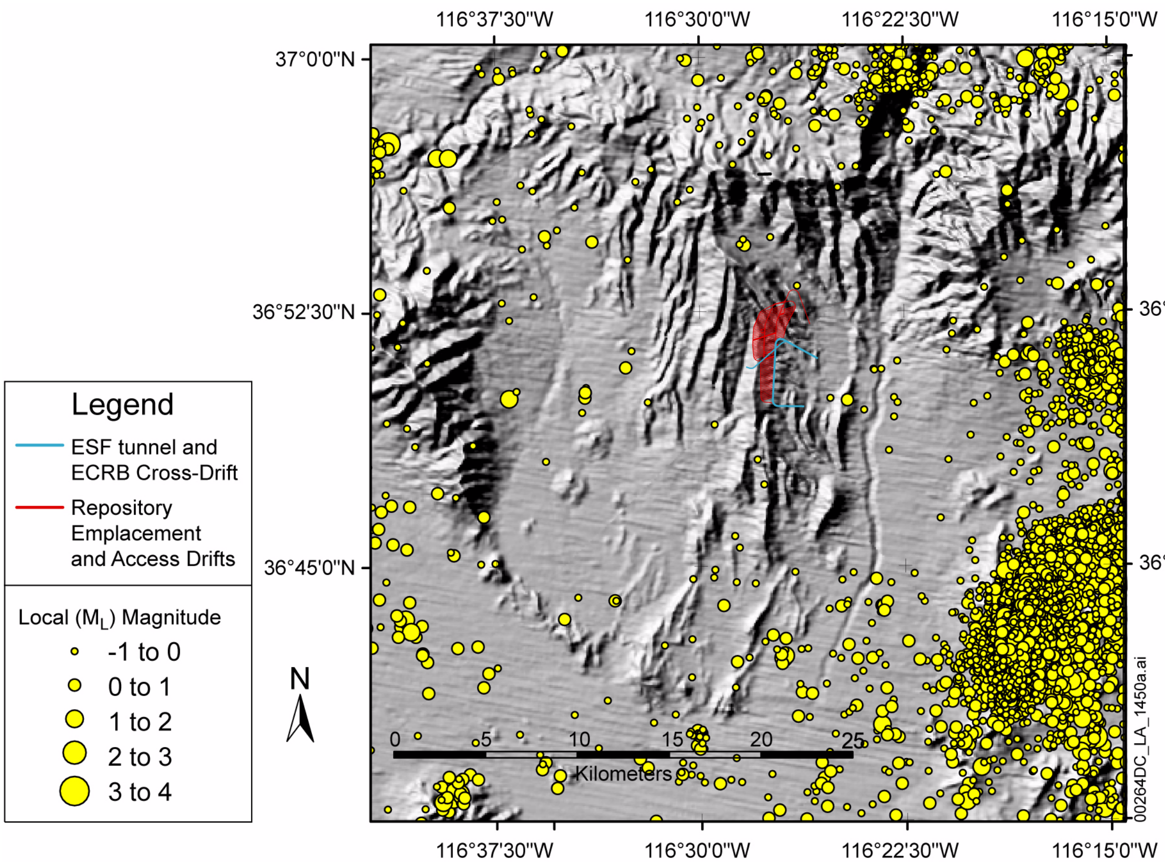

Figure 2.2-19. Seismicity at Yucca Mountain from October 1, 1995, to September 30, 2002

NOTE: The large number of detected earthquakes southeast of Yucca Mountain are mainly small magnitude (M_L less than 3) aftershocks of the June 1992 Little Skull Mountain earthquake. Improved seismic monitoring capabilities instituted in 1995 result in recording large numbers of very small magnitude earthquakes.

Source: Modified from BSC 2004j, Figure 4-22.

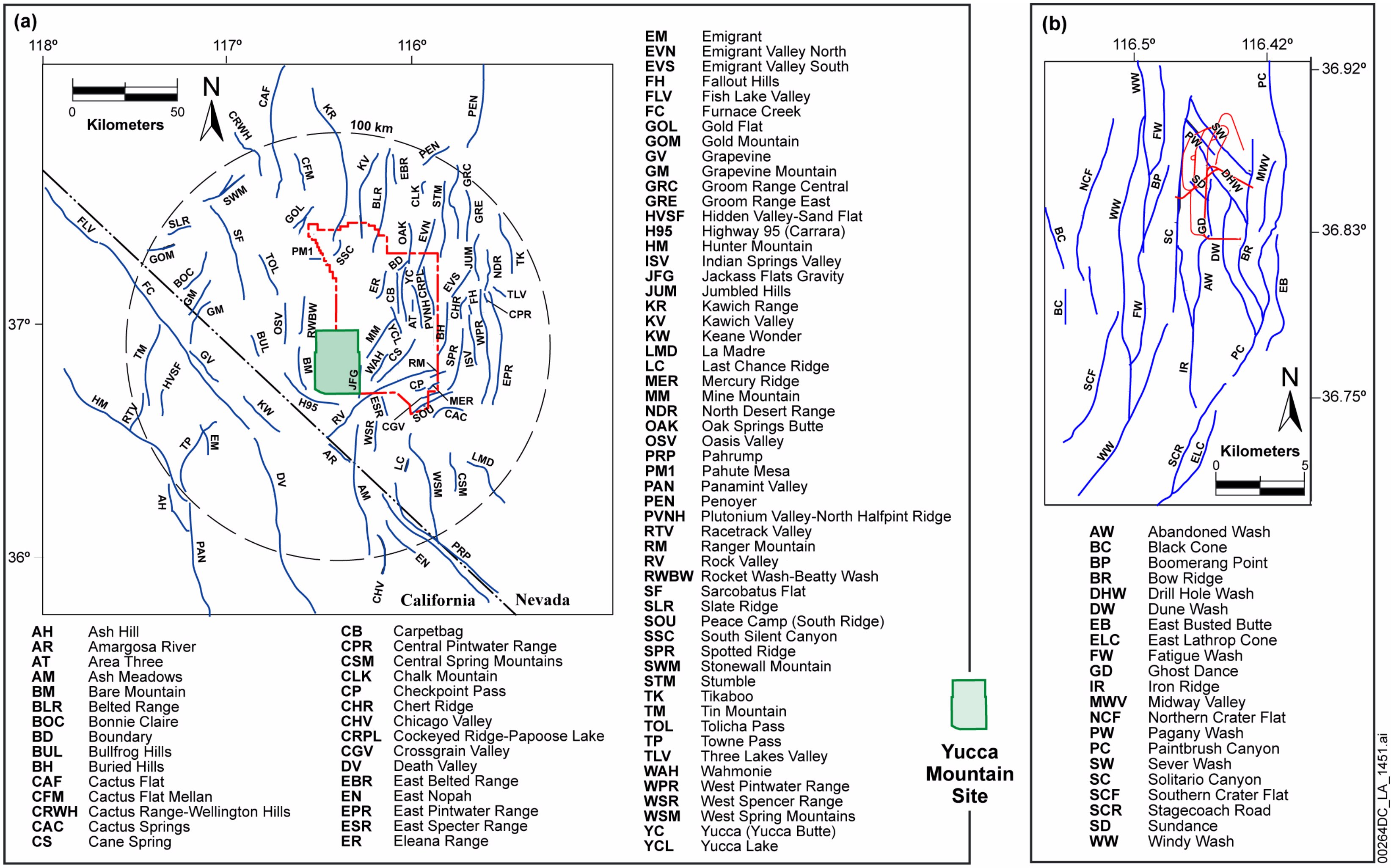

Figure 2.2-20. Known or Suspected Quaternary Faults and Other Notable Faults in the Yucca Mountain Region

NOTE: (a) Known or suspected Quaternary faults within 100 km of Yucca Mountain. (b) Detail of (a) showing known or suspected faults and other notable faults near Yucca Mountain.

Source: Modified from BSC 2004j, Figure 4-23.

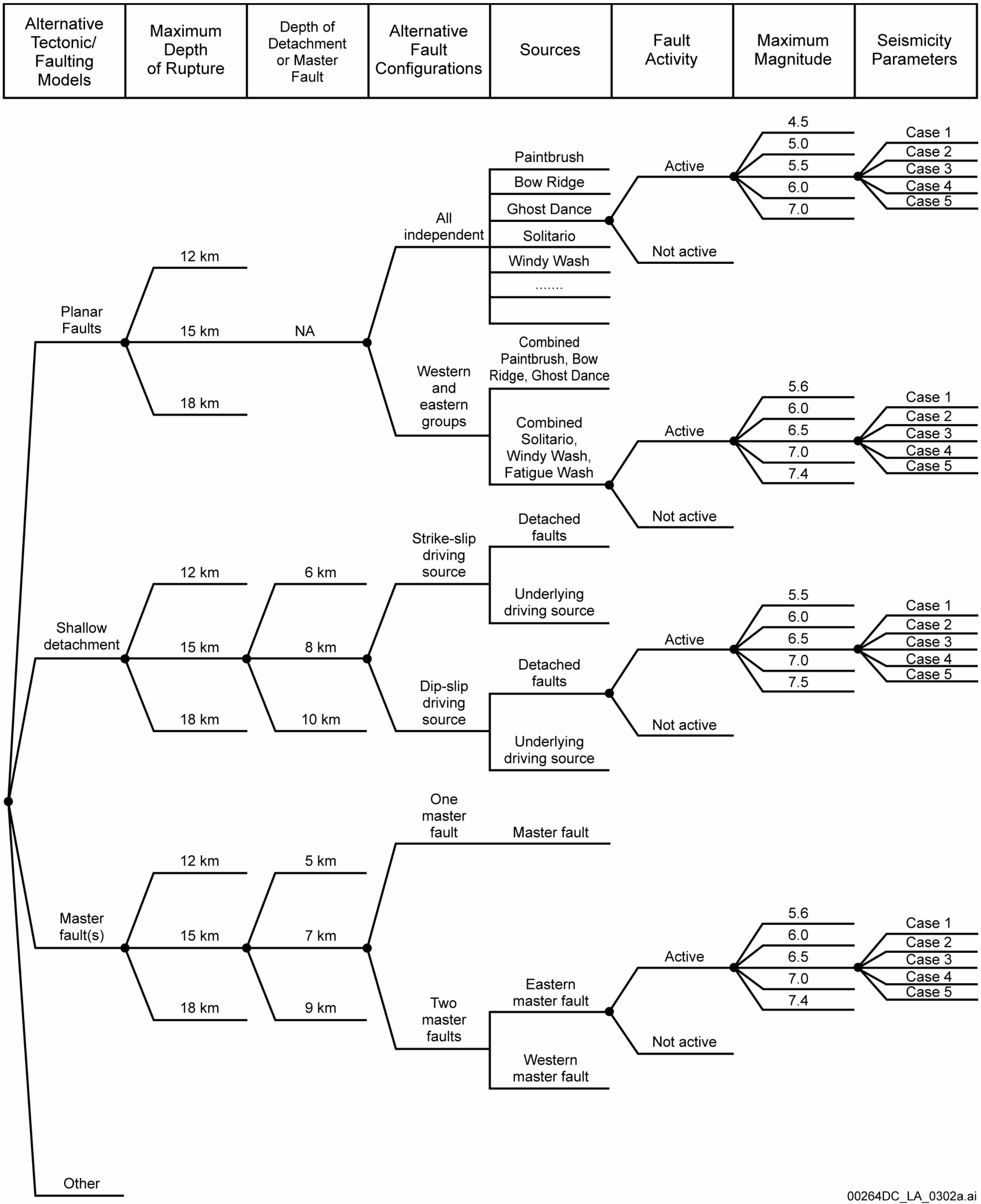

Figure 2.2-21. Example Logic Tree for Expressing the Uncertainty in Characterizing Local Fault Sources

Source: CRWMS M&O 1998a, Figure 4-2.

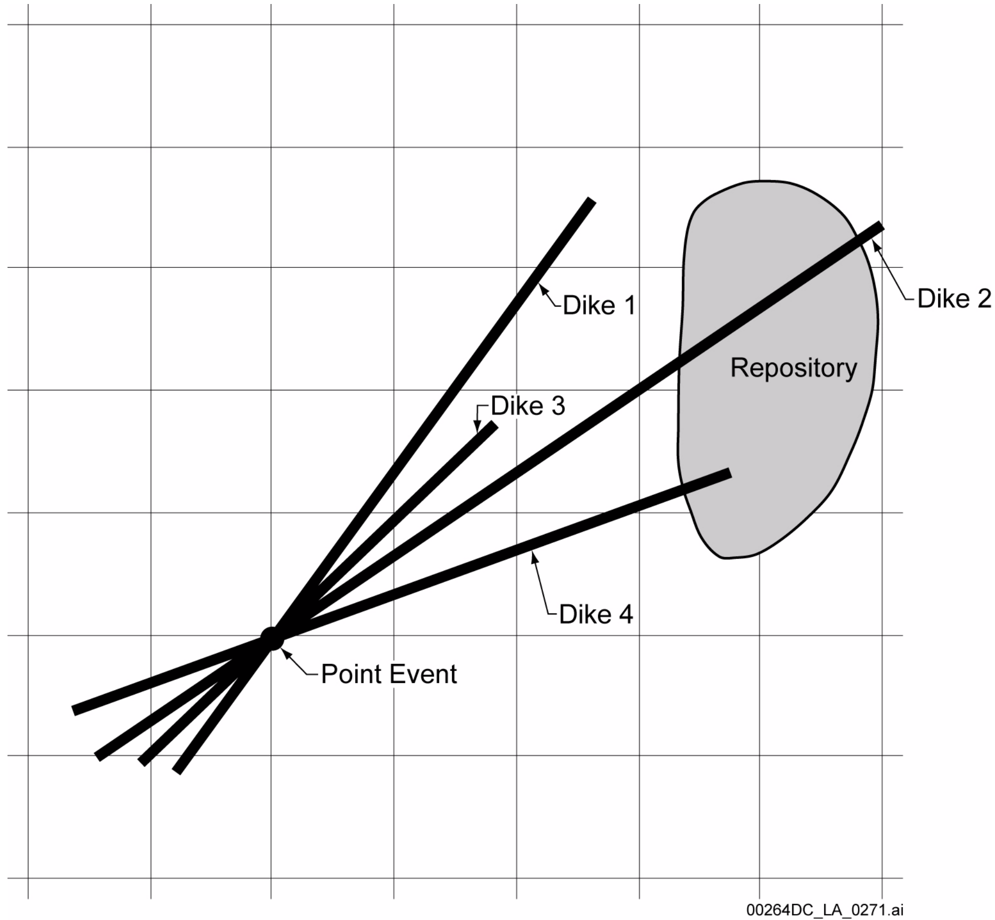

Figure 2.2-22. Schematic Illustrating Procedure for Computing the Frequency of Intersection of the Repository by a Dike or Dikes

NOTE: For illustration only.

Source: Modified after BSC 2004k, Figure 6-8.

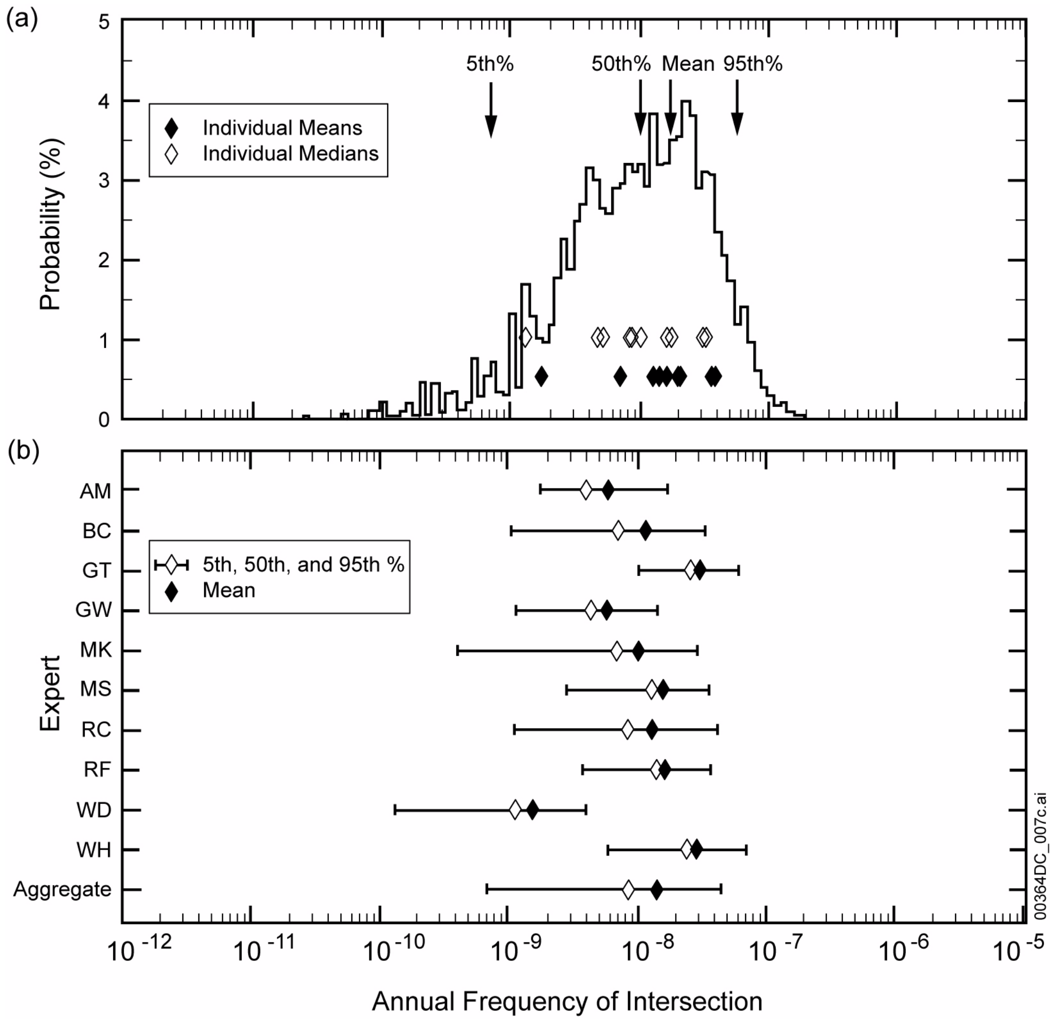

Figure 2.2-23. Annual Frequency of Intersecting the Repository Footprint

NOTE: (a) Aggregate distribution and median and means for individual PVHA expert interpretations. (b) Range for 5th to 95th percentiles for results from individual PVHA expert interpretations compared to range for aggregate distribution. Two-letter code indicates initials of experts. Expert names and affiliations are listed in *Characterize Framework for Igneous Activity at Yucca Mountain*, Nevada (BSC 2004k, Table 6-3).

Source: Modified after BSC 2004k, Figure 6-18.

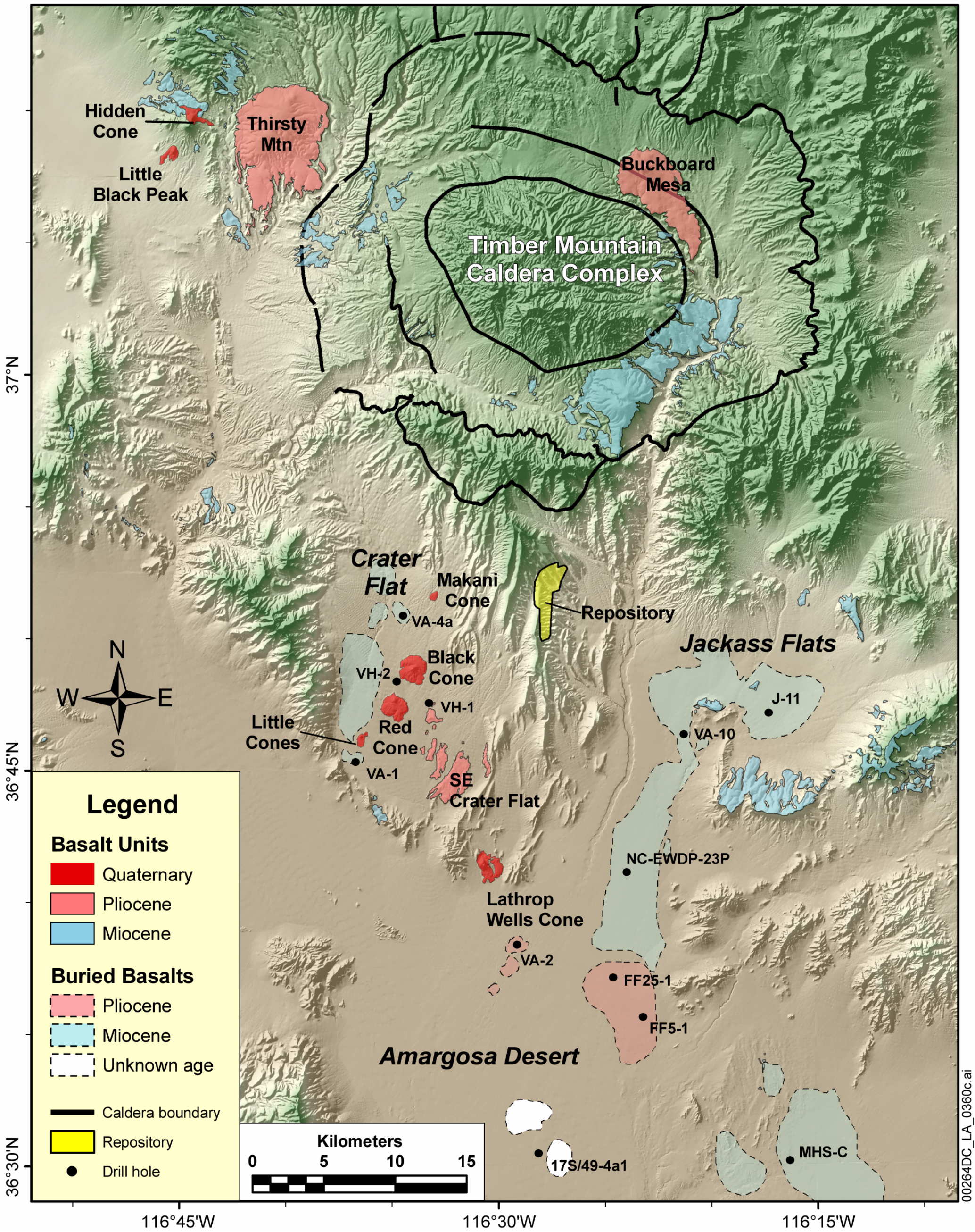

Figure 2.2-24. Distribution of Quaternary, Pliocene and Miocene Basaltic Rocks in the Yucca Mountain Region

NOTE: All drill holes shown encountered buried basalt. Distribution of buried basalt (areas enclosed by dashed lines) based on interpretation of aeromagnetic data and drill hole results. Buried basalts are Miocene in age except for approximately 3.8-Ma basalts in drill holes VH-1, VA-2, FF5-1 and FF-25-1 in Crater Flat and northern Amargosa Desert.

Source: Based on information presented in Slate et al. 2000; anomaly locations in DTN: LA0411AC831142.001; and locations of anomalies due to basalt in DTN: MO0606SMFGLIAF.000; SNL 2007l, Table 6-2; Fleck et al. 1996; Perry et al 1998; Heizler et al. 1999; DTN: GS070508318512.003.

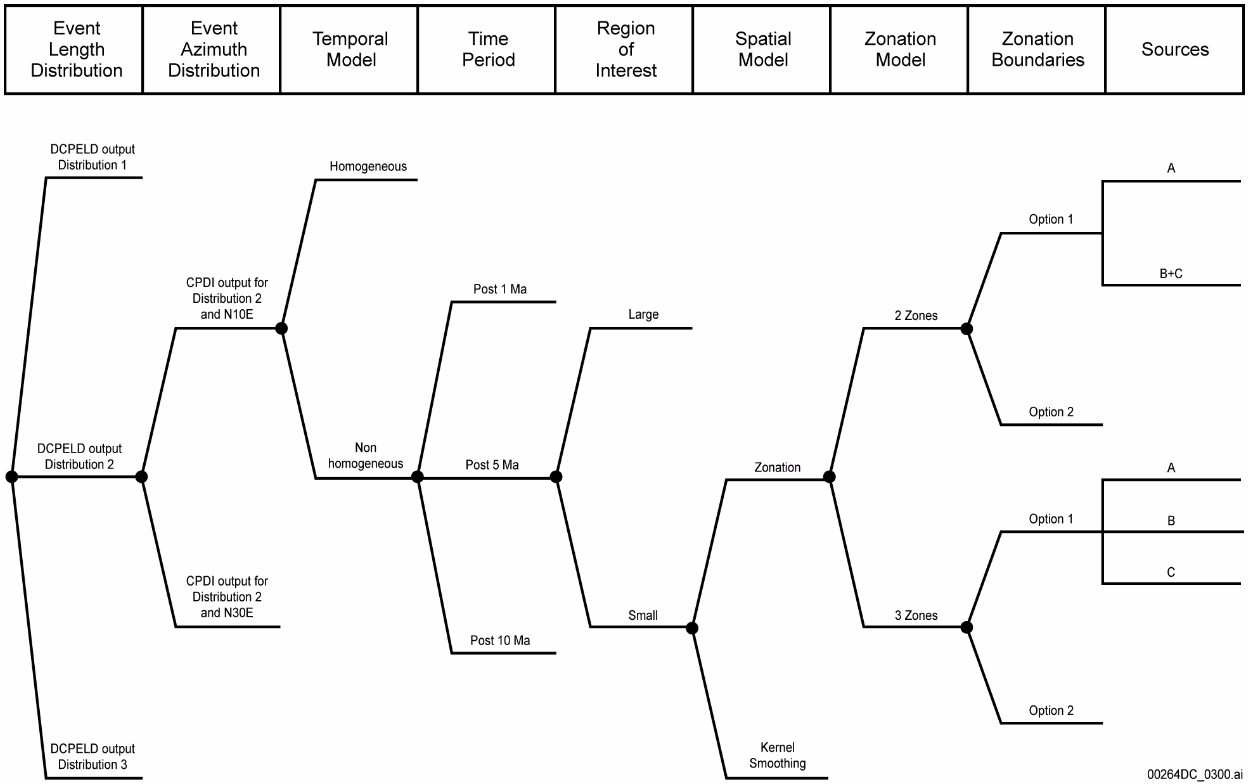

Figure 2.2-25. Logic Tree Structure Used to Characterize Uncertainty in a Volcanic Event

Source: BSC 2004k, Figure 6-12a.

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