DOC.20080211.0010

QA: QA

ANL-WIS-MD-000026 REV 00

February 2008

Features, Events, and Processes for the Total System Performance Assessment: Methods

Prepared for:
U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Office of Repository Development
1551 Hillshire Drive
Las Vegas, Nevada 89134-6321

Prepared by:
Sandia National Laboratories
OCRWM Lead Laboratory for Repository Systems
1180 Town Center Drive
Las Vegas, Nevada 89144

Under Contract Number
DE-AC04-94AL85000

DISCLAIMER

QA: QA

Features, Events, and Processes for the Total System Performance Assessment: Methods

ANL-WIS-MD-000026 REV 00

February 2008

Scientific Analysis/Calculation Signature Page/Change History

1. Total Pages: ~~78~~ 80

Complete only applicable items.

2. Document Title			
Features, Events, and Processes for the Total System Performance Assessment: Methods			
3. DI (Including Revision No. and Addendum No.)			
ANL-WIS-MD-000026 REV 00			
	Printed Name	Signature	Date
4. Originator	Carl Axness/Kathy Turnham	Kathy M. Turnham / Stephanie Kuzio for Carl Axness	2/7/08
5. Checker	Dwayne Kicker	C. Dwayne Kicker	2/7/2008
6. QCS/Lead Lab QA Reviewer	Charles D. Beach	Charles D. Beach	2-7-08
7. Responsible Manager/Lead	Peter Swift	Peter Swift	Feb 7, 2008
8. Responsible Manager	Stephanie Kuzio	Stephanie Kuzio	Feb 7, 2008
9. Remarks			

Change History

10. Revision No. and Addendum No.	11. Description of Change
Rev 00	This methods report and its companion analysis report, *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008 [DIRS 183041]), describe the continuation of FEP analysis and scenario development, initially documented in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800]). These two reports supersede: *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800); *Evaluation of Features, Events, and Processes (FEP) for the Biosphere Model* (BSC 2005 [DIRS 174107]); *Clad Degradation – FEPs Screening Arguments* (BSC 2004 [DIRS 170019]); *Features, Events, and Processes: Disruptive Events* (BSC 2005 [DIRS 173981]); *Engineered Barrier System Features, Events, and Processes* (BSC 2005 [DIRS 175014]); *Features, Events, and Processes: System Level* (BSC 2004 [DIRS 170021]); *Features, Events, and Processes in SZ Flow and Transport* (BSC 2005 [DIRS 174190]); *Features, Events, and Processes in UZ Flow and Transport* (BSC 2005 [DIRS 174191]); *Waste Form Features, Events, and Processes* (BSC 2004 [DIRS 170020]); *Screening of Features, Events, and Processes in Drip Shield and Waste Package Degradation* (BSC 2005 [DIRS 174995]).

INTENTIONALLY LEFT BLANK

CONTENTS

CONTENTS (Continued)

Page

FIGURES

TABLES

INTENTIONALLY LEFT BLANK

ACRONYMS AND ABBREVIATIONS

BSC	Bechtel SAIC Company, LLC
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
DTN	data tracking number
EBS	Engineered Barrier System
FEPs	features, events, and/or processes
NEA	Nuclear Energy Agency
NRC	U.S. Nuclear Regulatory Commission
NUREG	nuclear regulatory guides (from the NRC)
RMEI	reasonably maximally exposed individual
TSPA-LA	Total System Performance Assessment for the License Application
TSPA-SR	Total System Performance Assessment for Site Recommendation
YMP	Yucca Mountain Project

INTENTIONALLY LEFT BLANK

1. PURPOSE

The purpose of this methods report is to document: (1) the origin, and the methods used in the development of a comprehensive list of features, events, and/or processes (FEPs) that could potentially affect the postclosure performance of the Yucca Mountain disposal system; (2) the methodology and guidance used to screen FEPs for inclusion or exclusion from Total System Performance Assessment for the License Application (TSPA-LA) analysis; (3) the methodology and guidance used to create scenario classes; and (4) compliance with NUREG-1804 (NRC 2003 [DIRS 163274]) acceptance criteria outlined in Section 4.2.1. The conclusions drawn from this report include a list of FEPs identified for consideration in the TSPA analysis, criteria used to screen the FEPs for inclusion/exclusion in the TSPA-LA analysis, guidance to develop the scenario class designations, and, text describing compliance of these activities with the applicable acceptance criteria.

A performance assessment is required to demonstrate compliance with the postclosure performance objective for the U.S. Department of Energy (DOE) Yucca Mountain Project (YMP) as stated in 10 CFR 63.2 [DIRS 178394; DIRS 180319]. A performance assessment means 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; and

(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.

In addition, the performance assessment is required to "provide the technical basis for either inclusion or exclusion of specific features, events, and processes in the performance assessment" as stated in 10 CFR 63.114 [DIRS 178394]. This methods report describes the FEP analysis methodology and scenario development approach for the TSPA-LA, consistent with the regulatory-specified requirements and definitions.

The technical basis for exclusion or inclusion of each of the FEPs applicable to the Yucca Mountain disposal system and the TSPA-LA model is presented in a companion report, *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008 [DIRS 183041], Section 6).

1.1 PLANNING AND DOCUMENTATION

This methods report followed documentation requirements described in *Technical Work Plan for the Performance Assessment Features, Events, and Processes* (SNL 2007 [DIRS 184327]). This report deviates from the technical work plan (SNL 2007 [DIRS 184327]) only by superseding *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800]) upon approval of this document.

1.2 SCOPE

This methods report describes the current YMP technical development of the list of FEPs used in the 2007 TSPA-LA analysis, beginning from the completion of the 2005 report, *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800]). The technical framework for the continued development of FEPs and scenario classes resumes where the above referenced document left off. New proposed regulations, new repository design considerations, and new technical information, have necessitated the continued development and refinement of the FEPs listed in the 2005 FEP document.

This report, together with its companion report *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008 [DIRS 183041]), supersede the following documents:

- *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800])
- *Evaluation of Features, Events, and Processes (FEP) for the Biosphere Model* (BSC 2005 [DIRS 174107])
- *Clad Degradation – FEPs Screening Arguments* (BSC 2004 [DIRS 170019])
- *Features, Events, and Processes: Disruptive Events* (BSC 2005 [DIRS 173981])
- *Engineered Barrier System Features, Events, and Processes* (BSC 2005 [DIRS 175014])
- *Features, Events, and Processes: System Level* (BSC 2004 [DIRS 170021])
- *Features, Events, and Processes in SZ Flow and Transport* (BSC 2005 [DIRS 174190])
- *Features, Events, and Processes in UZ Flow and Transport* (BSC 2005 [DIRS 174191])
- *Waste Form Features, Events, and Processes* (BSC 2004 [DIRS 170020])
- *Screening of Features, Events, and Processes in Drip Shield and Waste Package Degradation* (BSC 2005 [DIRS 174995]).

This report and *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008 [DIRS 183041]) do not supersede the 2004 document, *Screening Analysis of Criticality Features, Events, and Processes for License Application* (BSC 2004 [DIRS 168556]), but they do consolidate information from an updated Criticality FEP analysis documented in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008 [DIRS 173869]). The superseding documents collectively, along with

Development of the Total System Performance Assessment-License Application Features, Events, and Processes (BSC 2005 [DIRS 173800]), support the analysis and methodology used in developing of the 2007 YMP FEP list found in Table 7-1.

For TSPA-LA, FEP analysis and scenario development corresponds with the areas of review, review methods, and acceptance criteria outlined in NUREG-1804 (NRC 2003 [DIRS 163274], Sections 2.2.1.2.1.1, 2.2.1.2.1.2, and 2.2.1.2.1.3). Five steps have been identified for the YMP and are outlined below:

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 will be included (screened in) or excluded (screened out) from the YMP Total System Performance Assessment analysis.

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

4. Screen the scenario 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 following performance assessments conducted to demonstrate compliance with proposed 10 CFR 63.311 and 10 CFR 63.321 [DIRS 178394]; and 10 CFR 63.331 [DIRS 180319].

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

The first four steps in the YMP approach are based on the organization of the acceptance criteria presented in NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3). The fifth step described above, while not specifically included in the earlier referenced section was added for clarity and completeness of the YMP process.

FEP analysis includes: FEP identification and classification (step 1), and FEP screening (step 2). These steps address scenario analysis acceptance criteria 1 and 2, respectively, as outlined in NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3). This methods report will address the FEP identification and classification step, in addition to identifying the criteria used to screen the FEPs (included or excluded). Once FEPs are screened for the TSPA, they are aggregated into scenario classes in order to be implemented into the model analysis (step 3). This report describes the methodology applicable to identify the scenario classes, and therefore, scenario analysis acceptance criterion 3 from NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3) is partially addressed in this report. However, the specifics of the TSPA-LA scenario class formation and screening are described in more detail in *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008 [DIRS 183478], Sections 6 and 6.1.2).

The approach for identifying and classifying FEPs, relevant to the YMP TSPA-LA is described in Section 6.1. Section 6.2 addresses the methodology used for the process of FEP screening. Section 6.3 describes the scenario class formation. Actual FEP screening results are reported in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008 [DIRS 183041], Section 6). Scenario screening results (step 4), and implementation of the scenario classes (step 5) are addressed in *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008 [DIRS 183478], Section 6).

Summaries of the identification of the TSPA-LA FEPs, screening criteria, and scenario classes are provided in Section 7. Section 7.1 provides a discussion of how the current TSPA-LA FEP identification and scenario class formation are consistent with the regulations in 10 CFR Part 63 [DIRS 180319], and addresses the relevant Nuclear Regulatory Commission (NRC) scenario analysis acceptance criteria in NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3). Appendix A is a glossary of terms as they are used in this methods report.

FEPs are defined in NUREG-1804 as follows (NRC 2003 [DIRS 163274], Section 3):

- A feature is an object, structure, or condition that has a potential to affect disposal system performance
- An event is 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 to the period of performance
- A process is 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.

The intended uses for this report are as follows:

- Promote transparency, traceability, and reproducibility of the FEP analysis and scenario development process for TSPA-LA
- Provide a description of the process followed in FEP analysis, identification, screening and scenario development
- Identify a comprehensive list of FEPs potentially relevant to the postclosure performance of the Yucca Mountain repository
- Fully support the demonstration of compliance with scenario analysis acceptance criterion 1 and partial compliance with acceptance criterion 3 outlined in NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3).

Limitations on the use of this report are as follows:

- The identification of a comprehensive list of FEPs potentially relevant to the postclosure performance of the Yucca Mountain repository is based on site-specific information, design, and regulations, therefore, results described in this report are specific to the regulations, repository design, and identified processes for the YMP available at the time of the TSPA-LA.

INTENTIONALLY LEFT BLANK

2. QUALITY ASSURANCE

Development of this methods report and supporting analyses are subject to the Office of Civilian Radioactive Waste Management quality assurance program as identified in *Technical Work Plan for the Performance Assessment Features, Events, and Processes* (SNL 2007 [DIRS 184327], Section 8.1).

Approved quality assurance procedures were used to conduct and document the activities described in this report as directed by the technical work plan (SNL 2007 [DIRS 184327], Section 4). This work constitutes a methods report, and the documentation was prepared in accordance with SCI-PRO-005, *Scientific Analyses and Calculations,* and related procedures and guidance documents as outlined in the technical work plan (SNL 2007 [DIRS 184327]). This technical work plan (SNL 2007 [DIRS 184327], Section 8.4) also identifies applicable controls for the electronic management of data during the analysis and documentation activities.

INTENTIONALLY LEFT BLANK

3. USE OF SOFTWARE

This methods report uses no computational software; therefore, this analysis is not subject to software controls. The analyses and arguments are based on guidance and regulatory requirements, the results of analyses presented and documented in other analysis reports, and other technical literature. Software and models used to support this report are cited for traceability and transparency purposes, but no software or models are used in completing any analyses original to this report.

The report was developed using only commercial off-the-shelf software. Microsoft Word 2000 and Microsoft Word 2003 were used for word processing and are exempt from qualification in accordance with IM-PRO-003 *Software Management*, Section 2.0.

INTENTIONALLY LEFT BLANK

4. INPUTS

SCI-PRO-004, *Managing Technical Product Inputs*, categorizes technical product input usage as either direct input or indirect input. Direct input is used to develop the results or conclusions in a technical product. Indirect input is used to provide additional information that is not used in the development of results or conclusions. Direct inputs are addressed in this section.

All direct inputs (data, parameters, and other information) used in this analysis are identified in Section 4.1. Direct inputs used in this methods report are obtained from controlled source documents and other sources in accordance with SCI-PRO-004. Criteria relevant to the FEP screening process are described in Section 4.2. Applicable codes and standards are identified in Section 4.3.

4.1 DIRECT INPUTS

The direct inputs are listed in Table 4-1. They represent those inputs, used in FEP identification, classification, FEP screening methodology, and scenario class formation, which are discussed in this report.

Table 4-1. Direct Inputs used in FEP Identification

Source	Input	Used In	Input Description
1) 66 FR 32074 [DIRS 155216]	p. 32105, item 3; p. 32127, item 10	Section 4.2.2.3.4	Human intrusion scenario, unintentional drilling and deliberate intrusion
2) 66 FR 55732 [DIRS 156671]	p. 55753	Section 4.2.2.3.3	Basis for 18-km boundary
3) DTN: LA0307BY831811.001 [DIRS 164713]	File: *pecdist-la.xls* Table 22	Sections 6.3 and 6.3.5	Probability of an igneous event intersecting the repository
4) DTN: MO0501BPVELEMP.001 [DIRS 172682].	File: *Bounded Horizontal Peak Ground Velocity Hazard at the Repository Waste Emplacement Level.xls*	Section 6.3.5	Probability of a 1 m/s seismic event
5) DTN: SN0704PADSGCMT.001 [DIRS 182122]	File: *DS GC Model Analysis_benign condition.xls*; File: *DS GC Model Analysis_aggressive condition.xls*	Section 6.3.5	Drip shield general corrosion models based on 2.5-year Titanium Grade 7 corrosion rates
6) DTN: MO0508SEPFEPLA.002 [DIRS 175064]	File: *FEPs_be.mdb*	Section 6.1.1	Initial FEP list for TSPA-LA
7) 10 CFR 63 [DIRS 180319]	10 CFR 63.102(j)	Section 6.3	Definition of event class
	10 CFR 63.102(i) and 10 CFR 63.305(a), (b), and (d)	Section 4.2.2.3.1	Characteristics of reference biosphere
	10 CFR 63.312	Section 4.2.2.3.3	Characteristics of the RMEI
	10 CFR 63.302	Section 4.2.2.3.3	Definition of accessible environment

Table 4-1. Direct Inputs used in FEP Identification (Continued)

Source	Input	Used In	Input Description
7) 10 CFR 63 [DIRS 180319] (continued)	10 CFR 63.302	Section 4.2.2.3.3	Definition of controlled area
	10 CFR 63.2	Section 4.2.2.3.2	Definition of geologic setting
	10 CFR 63.302	Section 4.2.2.3.4	Definition of human intrusion
	10 CFR 63.322	Sections 6.3 and 6.3.5	Definition of Human Intrusion Analysis
	10 CFR 63.102(i)	Section 4.2.2.3.3	Definition of the RMEI
	10 CFR 63.2	Section 4.2.2.3.1	Definition of reference biosphere
	10 CFR 63.322	Section 4.2.2.3.4	Regulatory provisions regarding human intrusion
	10 CFR 63.2	Section 6.1.3	Definition of a barrier
8) 70 FR 53313 [DIRS 178394]	10 CFR 63.302	Section 4.2.2.3.2	Definition of period of geologic stability
	10 CFR 63.321	Section 4.2.2.3.4	Criteria for evaluating human intrusion, earliest time driller recognizes single drip shield and waste package
	10 CFR 63.321	Sections 6.3 and 6.3.5	Definition of Human Intrusion Analysis
	10 CFR 63.114 (a)(4) and 10 CFR 63.342	Sections 4.2.2.1 and 6.2	Low probability criterion
	10 CFR 63.114(a)(5) and (6) and 10 CFR 63.342	Sections 4.2.2.2 and 6.2	Low consequence criteria
	10 CFR 63.342(a) and (c)	Section 4.2.2	Regulatory screening criteria
	10 CFR 63.342(c)	Sections 4.2.2.3 and 6.2	By-regulation criteria
	10 CFR 63.305(c)	Sections 4.2.2.3.1 and 4.2.2.3.2	Required characteristics of the reference biosphere
9) NRC 2003 [DIRS 163274]	Section 2.2.1.2.1.3	Section 7.1	Acceptance criteria
10) DTN: MO0701PASHIELD.000 [DIRS 180508]	File: Tables for DTN *Readme.doc*	Section 6.3	Probability of early drip shield or waste package failure, leading to early failure scenario
11) DTN: MO0703PASEISDA.002 [DIRS 183156]	File: *Seismic Damage Abstractions for TSPA Compliance Case.doc*	Section 6.3	Probability of seismic damage

4.2 CRITERIA

Criteria relevant to FEP identification, classification, screening, and scenario class formation are discussed in this section. These include review and acceptance criteria (Section 4.2.1) and regulatory screening criteria (Section 4.2.2).

4.2.1 Review and Acceptance Criteria

The review criteria relevant to the FEP process are described in NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1), and the bases for acceptance are stated as acceptance criteria. These criteria stem from applicable regulations in 10 CFR Part 63 [DIRS 180319]. NUREG-1804 (NRC 2003 [DIRS 163274]) acceptance criteria and their correlations to the regulations applicable to this report are listed in Table 4-2.

Table 4-2. Relationships of NRC Regulations to the Acceptance Criteria from NUREG-1804

Description of the Applicable Regulatory Requirement or Acceptance Criterion	10 CFR Part 63 [DIRS 180319]	NUREG-1804 (NRC 2003 [DIRS 163274])
	Regulatory Citation	Associated Criteria
Include data related to geology, hydrology, geochemistry, and geophysics	63.114(a)	2.2.1.2.1.3 Acceptance Criterion 1
Include information on the design of the EBS used to define parameters and conceptual models	63.114(a)	2.2.1.2.1.3 Acceptance Criterion 1
Compile a list of FEPs expected to materially affect compliance	63.102 (j) 63.114 (e) and (f) 63.342	2.2.1.2.1.3 Acceptance Criterion 1
Generate scenario classes that are representative of the range of futures that are potentially relevant to the licensing of the facility	63.102(j)	2.2.1.2.1.3 Acceptance Criterion 3

4.2.2 Regulatory Screening Criteria

This section describes the YMP FEP screening criteria used to identify FEPs that will be included or excluded from the TSPA-LA analysis (10 CFR 63.342 [DIRS 178394]). Screening criteria stem from applicable regulations in 10 CFR Part 63 [DIRS 180319], and those incorporated from 40 CFR Part 197 final rule (66 FR 32074 [DIRS 155216]), as listed in Table 4-1. The YMP FEP screening criteria are described in the following sections.

Subsequent to the development of the list of FEPs identified in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800]), a proposed rule was introduced in the Federal Register (70 FR 53313 [DIRS 178394]) that would amend the regulations governing the disposal of high-level radioactive waste in a proposed geologic repository at Yucca Mountain, Nevada. The proposed rule implements the Environmental Protection Agency proposed revised standards for the Yucca Mountain repository retaining the standards applicable to the first 10,000 years after disposal, and proposes to add separate requirements for the peak radiation dose after 10,000 years and within the period of geologic stability. This proposed rule has necessitated a FEP reanalysis for impact on the repository for the period beyond 10,000 years to geologic stability. According to 10 CFR 63.342(c) (70 FR 53313 [DIRS 178394]), performance assessments conducted to demonstrate compliance with the individual protection standard (10 CFR 63.311) and the individual protection standard for human intrusion (10 CFR 63.321) shall project the continued effects of all included FEPs beyond 10,000 years after closure until the period of geologic stability, including seismic and igneous events covered under the probability limits specified in 10 CFR 63.342(a) (70 FR 53313 [DIRS 178394]).

4.2.2.1 Low Probability Criterion

The proposed 10 CFR 63.114(a)(4) (70 FR 53313 [DIRS 178394], p. 53318) requires any performance assessment used to demonstrate compliance with 10 CFR 63.113 [DIRS 180319] for 10,000 years after disposal to "Consider only features, events, and processes consistent with the limits on performance assessment specified at §63.342." The proposed 10 CFR 63.342(a) (70 FR 53313 [DIRS 178394], pp. 53319 and 53320) 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 occurring within 10,000 years of disposal (less than one chance in 100,000,000 per year)."

10 CFR 63.342(b) (70 FR 53313 [DIRS 178394], p. 53319) 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)."

4.2.2.2 Low Consequence Criteria

Pursuant to 10 CFR 63.114(a)(5) and (6) (70 FR 53313 [DIRS 178394], p. 53318) any performance assessment used to demonstrate compliance with 10 CFR 63.113 [DIRS 180319] 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.

Having established the criterion for excluding very unlikely FEPs, 10 CFR 63.342(a) (70 FR 53313 [DIRS 178394], p. 53319) 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 [DIRS 178394], pp. 53319 and 53320).

4.2.2.3 By-Regulation Criteria

Certain FEPs specifically require inclusion in performance assessments conducted to demonstrate compliance with the individual protection standards for the period after 10,000 years after disposal but within the period of geologic disposal. In particular, the proposed 10 CFR 63.342 (c) (70 FR 53313 [DIRS 178394], pp. 53319 and 53320) 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 ground water.

(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.

If a FEP is inconsistent with, or contradicts, these regulations, the FEP can be specifically excluded by regulation from the TSPA (NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3, acceptance criterion 2)).

4.2.2.3.1 Reference Biosphere

Per 10 CFR 63.2 [DIRS 180319], the reference biosphere is defined as:

> The description of the environment inhabited by the reasonably maximally exposed individual. The reference biosphere comprises the set of specific biotic and abiotic characteristics of the environment, including, but not necessarily limited to, climate, topography, soils, flora, fauna, and human activities.

The characteristics pertaining to the reference biosphere are presented in 10 CFR 63.305(a), (b), and (d) [DIRS 180319], and 10 CFR 63.305(c) [DIRS 178394]:

(a) Features, events, and processes that describe the reference biosphere must be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site.

(b) DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of submission of the license application.

(c) DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system during the period of geologic stability and consistent with the requirements for performance assessments specified at § 63.342.

(d) Biosphere pathways must be consistent with arid or semi-arid conditions.

This is further supported by 10 CFR 63.102(i) [DIRS 180319], which states, "…The environment inhabited by the reasonably maximally exposed individual, along with associated human exposure pathways and parameters, make up the reference biosphere, as described in § 63.305." and "…Characteristics of the reference biosphere…are to be based on current human behavior and biospheric conditions in the region, as described in 10 CFR 63.305 and 10 CFR 63.312."

4.2.2.3.2 Geologic Setting

Per 10 CFR 63.2 [DIRS 180319], the geologic setting is defined as:

> The geologic, hydrologic, and geochemical systems of the region in which a geologic repository is or may be located.

The required characteristics of the reference biosphere are described in 10 CFR 63.305(c) [DIRS 178394] as:

> DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system during the period of geologic stability and consistent with the requirements for performance assessments specified at § 63.342.

The proposed rule 10 CFR 63.302 (70 FR 53313 [DIRS 178394], p. 53319) further defines the period of geologic stability 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.

4.2.2.3.3 Reasonably Maximally Exposed Individual (RMEI)

10 CFR 63.102(i) [DIRS 180319] states:

> The reasonably maximally exposed individual, as a hypothetical person living in a community with the characteristics of the Town of Amargosa Valley, is a representative person using water with average concentrations of radionuclides as described at § 63.312. The reasonably maximally exposed individual is selected to represent those persons in the vicinity of Yucca Mountain who are reasonably expected to receive the greatest exposure to radioactive material released from a geologic repository at Yucca Mountain. Characteristics of the … reasonably maximally exposed individual are to be based on current human behavior and biospheric conditions in the region, as described in § 63.305 and § 63.312.

The characteristics of the RMEI are given in 10 CFR Section 63.312 [DIRS 180319]:

> The RMEI is a hypothetical person who meets the following criteria:
>
> (a) Lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination;
>
> (b) Has a diet and living style representative of the people who now reside in the town of Amargosa Valley, Nevada;

(c) Uses well water with an average concentration based on an annual water demand of 3,000 acre-feet;

(d) Drinks 2 liters of water per day from wells drilled into the ground water at the location specified in paragraph (a); and

(e) Is an adult with metabolic and physiological considerations consistent with present knowledge of adults.

Pertinent to the definition of the RMEI is the spatial relationship between the repository and the RMEI, which must consider the areal extent of the accessible environment and of the controlled area. From 10 CFR 63.302 [DIRS 180319], the accessible environment is defined as "Any point outside of the controlled area…." In 10 CFR 63.302 [DIRS 180319], the controlled area is defined as:

1. The surface area, identified by passive institutional controls, that encompasses no more than 300 square kilometers. It must not extend farther:

   (i) South than 36° 40' 13.6661" North latitude, in the predominant direction of ground water flow; and

   (ii) Than five kilometers from the repository footprint in any other direction; and

2. The subsurface underlying the surface area.

The preamble to 10 CFR Part 63 (66 FR 55732 [DIRS 156671], p. 55753) states:

> At distances less than 18 km to the Yucca Mountain site, there is evidence of intermittent or temporary occupation in modern (historic) times in and around the site—for prospecting or ranching (see ''Preliminary Performance-Based Analyses Relevant to Dose Based Performance Measures for a Proposed Geologic Repository at Yucca Mountain,'' T. McCartin and M. Lee (eds.), *NUREG–1538*, 2001 (in press)). There also are a number of Native American archeological sites reported throughout NTS closer to the site than the Lathrop Wells location. However, the literature indicates that these were never permanently occupied, and most were abandoned by the end of the 1800's. Overall, the literature suggests many reasons for the absence of permanent inhabitation at distances much closer than 18 km to the site—unfavorable agricultural conditions, inhospitable terrain, the scarcity of mineral resources, and limitations on water availability.

4.2.2.3.4 Human Intrusion

Human intrusion is defined in 10 CFR 63.302 [DIRS 180319] as "…breaching any portion of the Yucca Mountain disposal system, within the repository footprint, by any human activity."

The proposed 10 CFR 63.321 (70 FR 53313 [DIRS 178394], p. 53319) standard for human intrusion requires that:

(a) DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion (see 10 CFR 63.322 [DIRS 180319]) 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 of 63.322.

Specific regulatory provisions (10 CFR 63.322 [DIRS 180319]) regarding consideration of human intrusion states that:

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 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;

(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 preamble to 40 CFR Part 197 (66 FR 32074 [DIRS 155216], p. 32105, Item 3) states:

> Comments we received proposing alternative drilling frequencies and intentions, such as deliberately drilling into the repository, did not provide a sufficient rationale to abandon the NAS recommendations and we therefore retained our original framing for the scenario.

And the preamble to 40 CFR Part 197 (66 FR 32074 [DIRS 155216], p. 32127, Item 10) states:

> Some comments suggested that there is a strong possibility for deliberate intrusion into the repository to access its contents as possible resources. We believe that there is no useful purpose to assessing the consequences of deliberate intrusions because in that case the intruders would be aware of the risks and consequences and would have decided to assume the risks.

Human intrusion analysis is specifically excluded from the individual protection requirements by definition of the "undisturbed Yucca Mountain disposal system" described in 10 CFR 63.311(a) [178394]. By the same token, human intrusion analysis is also excluded from the groundwater protection requirements because of the definition of "undisturbed performance" used in 10 CFR 63.331 [DIRS 180319].

4.3 CODES, STANDARDS, AND REGULATIONS

The following applicable regulatory requirements are discussed in Section 4:

- 10 CFR Part 63 (70 FR 53313 [DIRS 178394])
- 10 CFR Part 63 [DIRS 180319]
- NUREG-1804 (NRC 2003 [DIRS 163274])
- 66 FR 55732 [DIRS 156671]
- 66 FR 32074 [DIRS 155216].

5. ASSUMPTIONS

No assumptions were identified that apply to the FEP screening methodology and criteria development set forth in this document.

INTENTIONALLY LEFT BLANK

6. YUCCA MOUNTAIN PROJECT APPROACH TO FEP ANALYSIS AND SCENARIO CLASS DEVELOPMENT

As stated in Section 1, FEP analysis and scenario development is a five-step process that corresponds with the acceptance criteria outlined in NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3).

For underground disposal of radioactive waste, postclosure performance assessment is an iterative process that includes scenario development, model development, and consequence analysis. It is generally accepted that the process of identifying, classifying and screening potentially relevant FEPs is a key activity supporting scenario development (NEA 1992 [DIRS 100479], pp. 11 to 14, and 22; NEA 1999 [DIRS 152309] p. 11; NEA 1999 [DIRS 169902], p. 8).

The final report of the Nuclear Energy Agency (NEA) Performance Assessment Advisory Group (NEA 1992 [DIRS 100479]) provides a summary of scenario development methods and their application up to approximately 1990. The report of the NEA Working Group on the development of an International FEP Database (NEA 1999 [DIRS 152309]) provides a follow-up summary of work, up to approximately 1997. These methods provide details about the different approaches to FEP analysis and scenario development.

In the late 1980s and early 1990s, FEP development was performed with project specific (rather than generic) lists developed in several different countries. Continuing FEP analysis in the mid-1990s focused on the completeness of those FEP lists. These activities are summarized in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800], Section 2 and Tables 2-1 to 2-4). These activities resulted in FEP lists from the following countries:

- Canada (Goodwin et al. 1994 [DIRS 100983])
- U.K. (Miller and Chapman 1993 [DIRS 100996])
- Sweden (Chapman et al. 1995 [DIRS 100970])
- Switzerland (Nationale Genossenschaft fur die Lagerung Radioaktiver Abfalle (NAGRA 1994 [DIRS 124260]))
- U.S. (DOE 1996 [DIRS 100975]).

Version 1.0 of the NEA International FEP Database (SAM 1997 [DIRS 139333]) documented in NEA (1999 [DIRS 152309]) contains a FEP list derived from these 5 lists as well as from two predecessor lists: Sweden (Andersson et al. 1989 [DIRS 100956], and NEA 1992 [DIRS 100479], pp. 24 and 25). This International FEP list formed an initial basis for the YMP FEP list.

Scenario development forms a link between the list of FEPs identified as applicable to performance assessment and the modeling and consequence calculations. Scenario class formation therefore, depends on the kinds of FEPs under consideration in addition to the types of calculations and models used in the TSPA analysis.

Per SCI-PRO-005, Attachment 2, direct inputs used in an analysis and/or model report are identified in Section 4. Corroborative information (indirect inputs) is cited in this Section, where relevant to support the direct inputs and to provide background and ancillary information for the analyses.

6.1 YUCCA MOUNTAIN PROJECT FEP IDENTIFICATION AND CLASSIFICATION

In step 1 of the FEP analysis and scenario development process, FEPs potentially relevant to the 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 provide a structure for developing scenario classes. The identification and classification of a comprehensive list of FEPs potentially relevant to the postclosure performance for Yucca Mountain is an iterative process based on site-specific information, design, and regulations. 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. Confidence in the comprehensiveness of a FEP list (confidence that the identified 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.

FEP analysis was initiated to support Total System Performance Assessment for Site Recommendation (TSPA-SR) and continues in an effort to support the TSPA-LA. Historical information regarding FEP identification and classification for the YMP is summarized in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800]).

As described in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800], Section 3), an initial TSPA-SR list of FEPs relevant to Yucca Mountain was developed from the comprehensive NEA list of FEPs from radioactive waste disposal programs in other countries (see Freeze et al. 2001 [DIRS 154365], Section 2.1 for details) and was supplemented with additional YMP-specific literature, results from technical analysis presented in YMP specific analysis reports, technical workshops, and reviews (see Freeze et al. 2001 [DIRS 154365], Sections 2.2 through 2.4 for details). A preliminary FEP classification process was applied (see Freeze et al. 2001 [DIRS 154365], Sections 3.2 and 5.5 for details), resulting in a final TSPA-SR list of 328 FEPs.

6.1.1 YMP FEP Identification

As summarized in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800], Section 2.1.1), there are four common FEP identification methods: (1) development from an existing list, (2) brainstorming by groups of relevant experts, (3) top-down elicitation from a classification scheme, and (4) hybrid procedures. These methods were applied both for the initial FEP identification activities supporting TSPA-SR and for the continuing FEP identification activities for TSPA-LA (BSC 2005 [DIRS 173800], Section 3.2). A summary of the application of these methods for TSPA-LA FEP identification is presented in the remainder of this section.

Preliminary FEP identification for TSPA-LA, which built upon the TSPA-SR list, was performed in two phases. The first phase was the refinement of the TSPA-SR FEP list to provide consistency with a revised classification scheme and for a more consistent level of detail between FEPs (BSC 2005 [DIRS 173800], Section 3). 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 or clarification of the applicability and scope of certain FEPs (BSC 2005 [DIRS 173800], Section 3.2.2).

The second phase was the identification of potential new FEPs and changes to existing FEPs based on updated or new technical information subsequent to the site recommendation (e.g., changes to design parameters, etc.) and audits against other recently published international lists. Implementation of this phase resulted in further changes to the overall FEP list, including technical content (BSC 2005 [DIRS 173800], Section 3.2.3).

The following bullets summarize the application of the four common FEP identification methods during the two phases of preliminary FEP identification for TSPA-LA:

- FEP identification started with the 328 FEPs analyzed for the site recommendation (method 1).
- The FEP list was revised for the license application using a hybrid procedure that included reclassification, refinement, and audits against other recently published international lists (method 4).
- 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 TSPA-LA FEP list (BSC 2005 [DIRS 173800], Appendix B) (method 3). 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 TSPA-LA FEP list. Therefore, each low-level functional element represented an alternate FEP or a group of related FEPs. A comparison of the TSPA-LA FEP list against the alternate FEP list was made (a) to build confidence that the TSPA-LA FEP list was complete, and (b) to identify any additional FEPs that might potentially enhance completeness.
- Additional refinements to the FEP list resulted from continuous iterative reviews and associated brainstorming (method 2) of the FEP list by the subject matter experts.

The two phases of preliminary TSPA-LA FEP identification were completed in the year 2005 and resulted in a preliminary TSPA-LA FEP list of 375 FEPs with associated preliminary screening decisions and rationales (DTN: MO0508SEPFEPLA.002 [DIRS 175064]). Subsequent to the development of that FEP list contained in the above data tracking number (DTN), new regulations, and changes in the design of the repository and disposal packages have occurred, necessitating a 'reanalysis' of FEPs for the TSPA-LA. This reanalysis involved a review of the FEP list in parallel with a re-evaluation of the screening decisions and rationales for each FEP. Specific activities related to the development of the FEP list include a general reevaluation of the FEP list (overall scope, names, and descriptions) and the integration of scope between FEPs by external experts, YMP subject matter experts, and licensing and performance assessment team members (method 2). This FEP list evaluation was performed iteratively, and in parallel, with a reevaluation of FEP screening bases (SNL 2008 [DIRS 183041], Section 6).

The reanalysis resulted in the elimination of one FEP from the list as a result of a change in the repository design. FEP 1.2.04.04.0C (Magma and Gas Flow through Magma Bulkheads) is no longer on the TSPA-LA list of potentially relevant FEPs, bringing the current total number of FEPs to 374. The reanalysis also resulted in minor changes to some FEP names and/or descriptions to better clarify the scope or intent of the FEP. For example, the name of FEP 2.3.11.02.0A has been changed from "Surface Runoff and Flooding" to "Surface Runoff and Evapotranspiration" to better represent the process described by the FEP. These changes to the FEP list are documented in a FEP log as described in Section 6.1.2.

The historical evolution of the list of FEPs relevant to Yucca Mountain, from the source FEPs through TSPA-SR and TSPA-LA, is summarized in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC (2005 [DIRS 173800], Appendix C). Identification of how source (NEA and YMP-specific) FEPs are captured by the current set of 374 FEPs is presented in DTN: MO0706SPAFEPLA.001 [DIRS 181613] in Table "FEPMappingNEAtoLA."

The combined and iterative use of all four common FEP identification methods from TSPA-SR through TSPA-LA supports the demonstration of comprehensiveness of the TSPA-LA FEP list.

6.1.2 YMP FEP Configuration Management

One condition of FEP analysis is that a FEP list must always be open to new FEPs. For TSPA-LA FEP analysis, the identification of design changes and/or new information that could result in new FEPs or changes to existing FEPs and the documentation of the evaluations of the resulting potential FEPs, were tracked using configuration management controls.

An outline for FEP configuration management using a 'Potential FEP Log' was presented in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800], Section 3.2.4). The configuration management approach consists of the following steps:

1. Identification of potential FEPs
2. Evaluation and resolution of potential FEPs
3. Tracking and documenting potential FEPs.

The term "potential FEP" is used to refer collectively to potential new FEPs and potential changes to existing FEPs. Potential FEPs represent possible changes to the overall scope of the FEP list. Potential FEPs can come from sources such as introduction of alternative conceptual models, design changes, and new technical information from internal project documents or from external documents (step 1). Potential FEPs must be formally evaluated (step 2) to determine whether a change to the FEP list is necessary.

The FEP Log is a tracking system (step 3) that documents the rationale for all potential changes to the FEP list subsequent to the final TSPA-SR FEP list. The complete list of potential changes is summarized in DTN: MO0706SPAFEPLA.001 ([DIRS 181613]) in Table "Potential FEP Log." Actual changes between the final TSPA-SR FEP list and the TSPA-LA FEP list (e.g., added or deleted FEPs, grammatical changes to FEP names and/or descriptions, new technical language that better describes the intent of the FEP, and/or changes required by new regulations or design requirements) are identified in DTN: MO0706SPAFEPLA.001 [DIRS 181613] in Table "FEP History File" and in the "Historical_Notes" field in Table "FEPs." Further details about the structure and content of these tables are presented in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008 [DIRS 183041], Appendix H).

6.1.3 YMP FEP Classification

Several different general classification schemes can be used to organize FEPs. Common classification schemes (NEA 1992 [DIRS 100479], 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 [DIRS 152309], p. 28) include by field of effect, by causative factors, and layered by creating a hierarchal 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-SR), FEP classification was derived from a Nuclear Energy Agency classification scheme (NEA 1999 [DIRS 152309], pp. 28 to 34; Freeze et al. 2001 [DIRS 154365], Section 3). It was general in nature and was based on a layered combination of several of the common classification schemes. Preliminary FEP classification for TSPA-LA, completed in the year 2005, implemented a revised classification scheme that was based on a Yucca Mountain–specific combination of location, fields of effect, radionuclide mobilization phenomena, and causative factors. These historical classification approaches, which used various combinations of the common general classification schemes, are described in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800], Section 3.1).

Preliminary FEP classification for TSPA-LA resulted in a preliminary FEP matrix (BSC 2005 [DIRS 173800], Section 3.1.2, and Figure 3-1). The FEP-matrix based classification structure makes use of two separate axes, one corresponding to repository-relevant features/components, and the other corresponding to repository-relevant processes and events. For the current TSPA-LA FEP classification, the axes of the preliminary FEP matrix (BSC 2005 [DIRS 173800], Figure 3-1) were updated to more directly correspond to the features that comprise the natural and engineered barrier characteristics.

A barrier is defined as "any material, structure, or feature" that: "prevents or substantially reduces the rate of movement of water or radionuclides from the Yucca Mountain repository to the accessible environment" or "prevents the release or substantially reduces the release rate of radionuclides from the waste" (10 CFR 63.2 [DIRS 180319]).

As described in *Postclosure Nuclear Safety Design Bases* (SNL 2008 [DIRS 177464], Sections 6.1.2 and 6.2.1), the Yucca Mountain repository may be considered in terms of its three physical barriers, the Upper Natural Barrier, the Engineered Barrier System (EBS) and the Lower Natural Barrier. Each of these barriers is composed of features/components. The Upper Natural Barrier consists of two natural features: (1) the topography and surficial soils and (2) the unsaturated zone above the repository (SNL 2008 [DIRS 177464], Section 6.2.2.1). The EBS features are: (1) emplacement drifts, (2) drip shields, (3) waste packages, (4) cladding, (5) waste forms and waste package internals, (6) waste package pallet, and (7) the ballast in the emplacement drift inverts (SNL 2008 [DIRS 177464], Section 6.2.2.2). The Lower Natural Barrier includes: (1) the unsaturated zone below the repository horizon, and (2) the saturated zone below the repository and downgradient from it, to the accessible environment (SNL 2008 [DIRS 177464], Section 6.2.2.3).

The updated FEP matrix, which incorporates the barriers and features identified above to support FEP classification, is presented in Table 6-1. Two additional features/components (biosphere and system) that do not directly relate to the capability of barriers are also included in Table 6-1. "Biosphere" is used to classify FEPs that are relevant to the calculation of dose to the RMEI. "System" is used to classify FEPs that are potentially relevant to the repository system as a whole. An additional EBS feature, backfill/seals, is also included in Table 6-1 for FEP classification.

The updated FEP matrix (Table 6-1) incorporates the following changes from the 2005 version:

- The features/components axis is organized according to the features of the three physical barriers (Upper Natural Barrier, EBS, Lower Natural Barrier). While the names and groupings of the some of the features have changed, no information was eliminated or changed in this new classification (e.g., ground support and excavation disturbed zone from the preliminary classification are captured within the updated features).

- On the processes/events axis, thermal processes are not treated separately but instead are coupled with the process affected by thermal conditions. For example, the processes are 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 and has been excluded from further consideration.

- A new event, early failure, has been added (see Section 6.3 for discussion).

Because a FEP generally consists of a process or event acting upon a feature, the FEP matrix intersections represent "boxes" for which potential FEPs may exist. For each of the matrix boxes that are a credible combination of the axes (i.e., the specified process/event could logically be expected to act upon the specified feature), there are associated FEPs. A mapping of the FEPs to the FEP matrix boxes (or more specifically, to the FEP matrix axis components) is available in DTN: MO0706SPAFEPLA.001 [DIRS 181613] in Table "FEPs" (in the "Matrix Row" and "Matrix Column" fields) and in Table "Matrix Secondaries." All FEPs are mapped to at least one matrix box, some broad-scoped or overarching FEPs are mapped to multiple boxes. This mapping represents logical, but necessarily subjective, relationships between the scope of each FEP and the scope of each matrix box. In general, the features relevant to each FEP are explicitly identified by the FEP name and/or FEP description and the FEP directly maps to matrix boxes associated with those features. In some broad-scoped FEPs (generally those associated with "emplacement drift" or "system"), where not all of the features are explicitly identified by the FEP name or FEP description, the FEP was still mapped to all implicitly relevant matrix boxes. This mapping of FEPs to the FEP matrix allows for a check of the completeness of the FEP list. The FEP matrix completeness check indicated that each "credible" box contained at least one FEP, and that each empty box either corresponded to a noncredible combination of features and processes/events, or was represented by a related box (e.g., "emplacement drift" boxes sometimes capture overarching FEPs related to, but not explicitly mapped to, the individual EBS feature boxes).

This FEP matrix completeness check augments the prior use of different classification schemes during the TSPA-SR and TSPA-LA iterations in providing additional confidence in the comprehensiveness of the FEP list.

Table 6-1. Matrix Used for Classification of Features, Events, and Processes

Yucca Mountain FEP Matrix			Processes							Events				
			Hydrologic and Thermal-Hydrologic	Chemical and Thermal-Chemical	Mechanical and Thermal-Mechanical	Microbiological	Radiological	Characteristics	Transport	Igneous	Seismic	Criticality	Early Failure	Human Intrusion
Repository Subsystem Physical Elements and Features	UNB	Topography and Surficial Soils												
		Unsaturated Zone Above												
	EBS	Emplacement Drifts												
		Backfill/ Seals												
		Drip Shield												
		Waste Package												
		Cladding												
		Waste Form												
		Pallet												
		Invert												
	LNB	Unsaturated Zone Below												
		Saturated Zone												
	Biosphere													
	System													

UNB = Upper Natural Barrier, EBS = Engineered Barrier System, LNB = Lower Natural Barrier.

The features and components in Table 6-1 are presented from top to bottom, by the likely path that water would take in reaching the waste, and the path radionuclides might take from the repository to the accessible environment. The grouping of the 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 class. This classification structure approximates the way the repository system is conceptualized, and the order that information flows within the TSPA model. A brief description of the processes and events identified in Table 6-1 follows:

- Hydrologic flow processes include precipitation, infiltration, runoff, unsaturated zone flow, flow diversion, capillarity, matrix imbibition, evaporation, condensation, and saturated zone flow.

- Chemical processes include those chemical processes that affect the degradation mechanisms of engineered features. These chemical processes include such detailed processes as dissolution, precipitation, reduction and oxidation, salt deliquescence, general corrosion, localized (or crevice) corrosion, alteration, and solubility.

- 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, floor heave, metamorphism, diagenesis, among others.

- 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, and the heat flux decreases with time. 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. The effects of these thermal processes 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 their corresponding effects on rock mass strength and degradation.

- Microbiological processes include the potential effects of microorganisms on other processes relevant to performance, such as microbial effects on chemistry.

- Radiological processes include the potential effects of ionizing radiation 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 RMEI and the resulting doses.

- Characteristics 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).

- 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. In addition, radionuclide transport due to atmospheric transport processes following an eruptive volcanic event is also considered in this category.

- Natural disruptive events that may affect the repository include igneous intrusion intersecting the repository, volcanic eruption from a volcanic vent that intersects the repository, seismic activity that produces vibratory ground motion, the EBS, and potential seismic activity, including fault displacement which affects the repository and the EBS. Other disruptive events that could potentially affect barriers are meteor or comet impacts, and explosion or crashes.

- Igneous intrusion considers the possibility that magma, in the form of a dike, could intrude into repository drifts, destroying drip shields and waste packages in those drifts intruded by the magma, exposing the waste forms to percolating water that could mobilize radionuclides from the waste forms and transport the radionuclides through the unsaturated zone and saturated zone. Volcanic eruption considers that a volcanic conduit (or conduits) invades the repository, destroys waste packages, and erupts at the land surface. The volcanic eruption disperses volcanic tephra and entrained waste under atmospheric conditions, and deposits the contaminated tephra on land surfaces where the contaminated tephra becomes subject to redistribution by soil and near surface hydrogeologic processes.

- Seismic ground motion concerns damage to waste packages and drip shields due to vibrating ground motion. Seismic fault displacement includes the effects of fault displacement on waste packages and drip shields.

- Criticality events include initiators of sequences of events or processes that could lead to configurations that have potential for criticality in the repository. For a criticality event to occur, the appropriate combination of materials (neutron moderators, neutron absorbers, fissile materials, or isotopes) and geometric configurations favorable to criticality must exist. During design, criticality analyses are performed to demonstrate that the initial emplaced configuration of the waste form remains subcritical, even under flooded conditions. The design basis configuration is considered to bound the various limiting configurations that would result for each of the criticality FEP scenarios (nominal, rockfall, seismic, igneous). Therefore, for a configuration to have potential for criticality, all of the following conditions must occur: (1) sufficient mechanical or corrosive damage to the waste package outer corrosion barrier to cause a breach, (2) presence of a moderator, i.e., water, (3) separation of fissionable material from the neutron absorber material or an absorber material selection error during the canister fabrication process, and (4) the accumulation (external) or presence of a critical mass of fissionable material.

- An early failure event 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. The waste package beneath the early failed drip shield are assumed to be susceptible to localized corrosion, which compromises the waste packages, exposing the waste forms to percolating water, and mobilizing radionuclides. The released radionuclides may then be transported out of the repository, moved down through the unsaturated zone to the saturated zone, and then be transported through the saturated zone to the accessible environment.

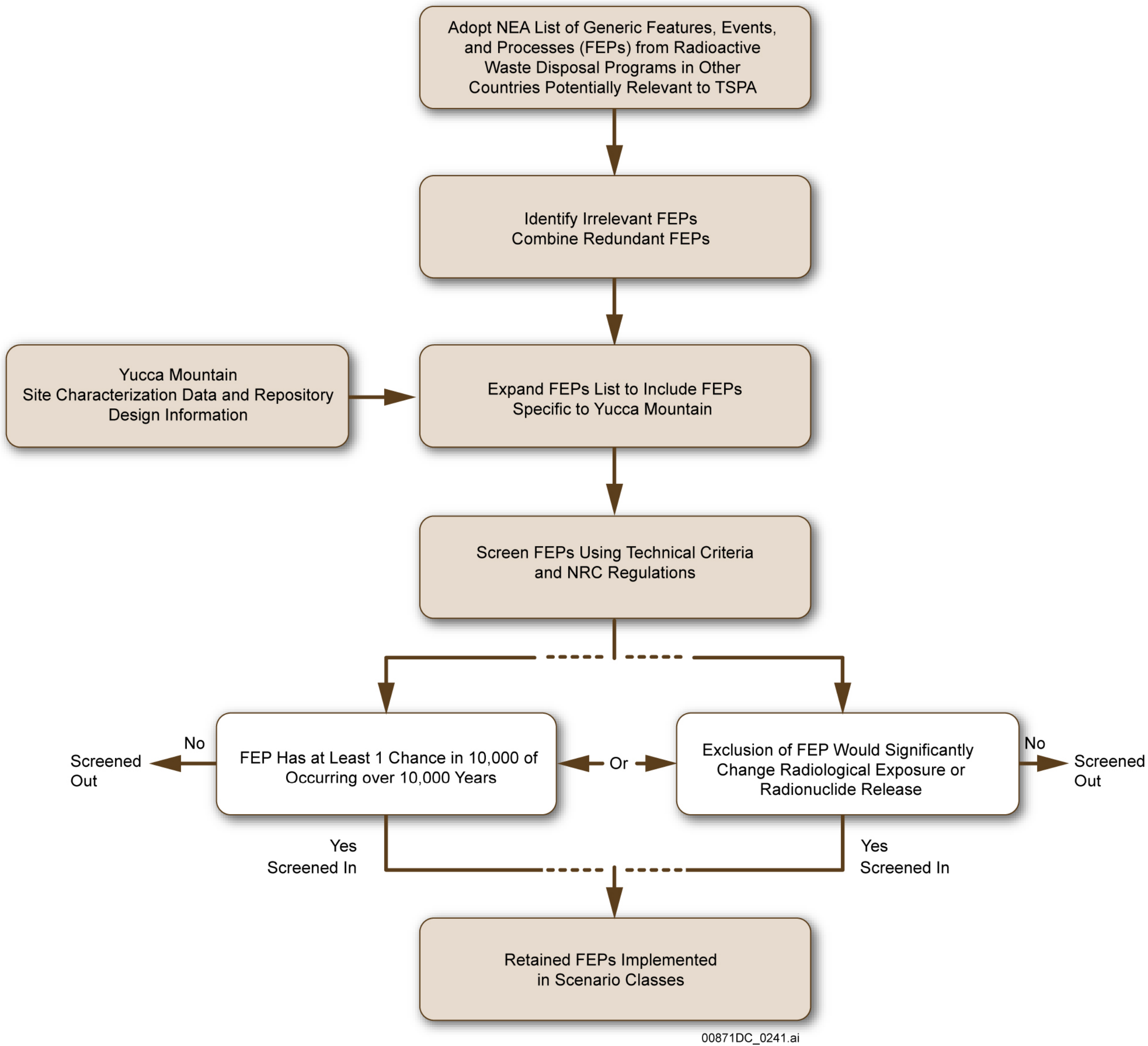
- The human intrusion event is a stylized calculation that simulates a future drilling operation in which an intruder drills a land-surface borehole using a drilling apparatus operating under the common techniques and practices currently employed in exploratory drilling for groundwater in the region around Yucca Mountain. During drilling, the drilling apparatus directly intersects a degraded drip shield and waste package causing a release of radionuclides subsequently carried by water into the saturated zone underlying Yucca Mountain. No releases are included which are caused by unlikely natural processes and events.

6.2 YUCCA MOUNTAIN PROJECT FEP SCREENING METHODOLOGY

In step 2 of the FEP analysis and scenario development process (Section 1.2), the list of FEPs identified and classified in step 1 is analyzed to determine: (1) which FEPs should be included in the performance assessment compliance analyses; and (2) which FEPs should be excluded.

The criteria, methodology, and results from the screening of the preliminary TSPA-LA FEP list are outlined in *Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800], Section 4.2). FEPs were screened to determine their inclusion and implementation into the then-current TSPA model, or determined to be excluded with a technical justification (in accordance with the exclusion criteria). Remembering that FEP analysis is an iterative process, the availability of new technical information, proposed new regulations, and new designs, subsequent to the preliminary screening in 2005, requires a new FEP screening analysis.

The new screening analysis will follow a similar approach as the preliminary analysis. FEP screening criteria presented in Section 4.2.2 will be used to screen the current list of FEPs. FEPs will be screened to determine whether they can be excluded (from TSPA-LA analysis) by reason of low probability, low consequence and/or by regulation. A FEP need only to satisfy one of the exclusion criteria to be considered excluded from the TSPA-LA analysis. FEPs that do not meet any of the exclusion criteria must be included (screened in) in the TSPA-LA analysis. The steps of this process are represented graphically in Figure 6-1. As described in Section 6.1.1, the new screening analysis will be performed in parallel with a reevaluation of the FEP list. As such, the new screening analysis will include reviews and updates from external experts, YMP subject matter experts, and licensing and performance assessment team members. The results of the FEP screening process are discussed in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008 [DIRS 183041], Section 6).



Source: SNL 2008 [DIRS 183478], Section 6.1.1, Figure 6.1.1-2.

Figure 6-1. Schematic Illustration of the Features, Events, and Processes Analysis Method

FEP screening criteria are summarized as follows:

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 occurring within 10,000 years of disposal (less than one chance in 100,000,000 per year)" (70 FR 53313 [DIRS 178394], pp. 53319 to 53320). In other words, very unlikely events have a frequency of occurrence 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 essentially occurs in the process of developing the implementation of relevant scenario classes for the assessments. 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 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 (6) (proposed), 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.

Inclusion of some FEPs in the TSPA-LA could potentially result in a decrease in the estimates of radiological exposures to the RMEI or radionuclide releases to the accessible environment, rather than an increase. As identified in 10 CFR 63.102(j) [DIRS 180319], the concept of a performance assessment includes the following:

> The features, events, and processes considered in the performance assessment should represent a wide range of both beneficial and potentially adverse effects on performance (e.g. beneficial effects of radionuclide sorption; potentially adverse effects of fracture flow on a criticality event). Those features, events, and processes expected to materially affect compliance with [10 CFR] 63.113(b) or be potentially adverse to performance are included, while events (event classes or scenario classes) that are very unlikely (less than one chance in 10,000 over 10,000 years) can be excluded from the analysis.

NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1) states:

> In many regulatory applications, a conservative approach can be used to decrease the need to collect additional information or to justify a simplified modeling approach. Conservative estimates for the dose to the reasonably maximally exposed individual can be used to demonstrate that the proposed repository meets U.S. Nuclear Regulatory Commission regulations and provides adequate protection of public health and safety. …The total system performance assessment is a complex analysis with many parameters, and the U.S. Department of Energy may use conservative assumptions to simplify its approaches and data collection needs. However, a technical basis … must be provided.

In some cases, a FEP that could only show improved performance may not be implemented in the TSPA-LA (e.g., where there is an insufficient technical basis for inclusion). In these cases, it is acceptable, on the basis of the above statements, to demonstrate that a beneficial FEP can only improve the performance (of an otherwise compliant system) and, therefore, that its omission cannot materially affect compliance. In these cases, FEPs that are demonstrated to have only beneficial effects on the radiological exposures to the RMEI, or radionuclide releases to the accessible environment, can be excluded on the basis of low consequence because they have no adverse effects on performance.

Accordingly, to the extent that a particular FEP has no significant adverse 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 (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 [DIRS 178394], 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 have no significant impact on the predicted dose in the TSPA. That is, even if the basis for screening can not rely solely on the low probability criterion (per 63.342(a)), the FEP may be excluded on low consequence in part because the FEP is not expected to occur and would not significantly impact the performance assessment results due to the combined effect of the low likelihood and low consequence.

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. These evaluations represent 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 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 the analysis to characteristics, concepts, and definitions (NUREG-1804 (NRC 2003 [DIRS 163274], 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 (Section 4.2.2.3).

Regulations require the 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 ground water.

(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 [DIRS 178394], pp. 53319 to 53320).

FEPs associated with the regulatory requirements above have been included in the appropriate performance assessments. No changes to screening decisions are necessary to address the inclusion of FEPs specified by proposed 10 CFR 63.342c (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. Specifically, the following FEPs address 10 CFR63.342(c)(1)(i):

- 1.2.02.03.0A, Fault Displacement Damages EBS Components

- 1.2.03.02.0A, Seismic Ground Motion Damages EBS Components
- 1.2.03.02.0B, Seismic-Induced Rockfall 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.

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

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

The following FEPs address 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.

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.

6.3 YUCCA MOUNTAIN PROJECT SCENARIO CLASS DEVELOPMENT METHODOLOGY

As noted in Section 1, the third step in the analysis of FEPs and scenarios is the aggregation of FEPs into appropriate event classes or scenario classes for the purpose of further screening or analysis. The concept of scenario classes is provided by 10 CFR 63.102(j) [DIRS 180319]. The objective of scenario class development for the 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. 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 that have an aleatory component). Note that, while the initial development of the scenario class formation is covered here, the specifics of the TSPA-LA FEP scenario class formation and screening are described in more detail in *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008 [DIRS 183478], Sections 6 and 6.1.2).

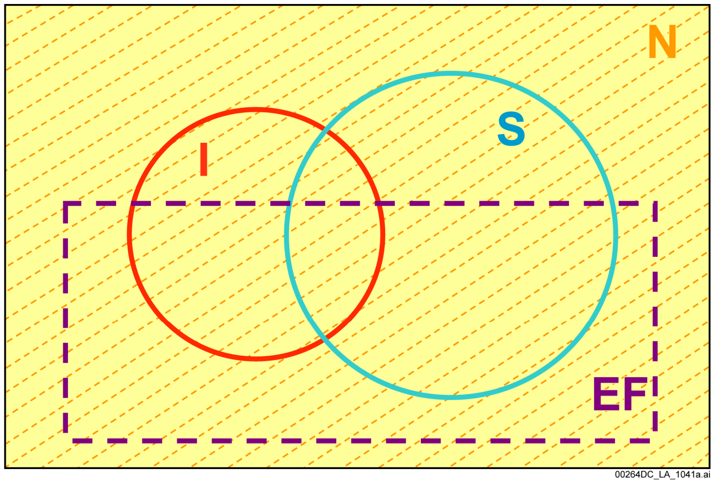
There is an essentially infinite number of possible future states, and for scenario development to be useful, it must generate scenario classes that are representative of the range of futures that are potentially relevant to the licensing of the facility and fit into a computational structure amenable for consequence analyses. 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. Scenario formation forms a link between the list of FEPs and the modeling and consequence calculations. Therefore, scenario class formation is influenced by the types of models and calculation tools available (NEA 1992 [DIRS 100479], p. 52) as well as the kinds of FEPs under consideration.

All FEPs screened in during the formal identification and screening for steps 1 and 2 are to be used for TSPA-LA scenario development and will be incorporated into scenario classes. A preliminary set of TSPA-LA scenario classes, derived from the TSPA-SR scenario classes, was previously identified to incorporate the preliminary list of included FEPs contained in DTN: MO0508SEPFEPLA.002 [DIRS 175064]. Based on this prior work, the scenario classes identified for inclusion in the TSPA-LA analysis are:

- Nominal
- Igneous
- Seismic
- Early Failure.

The nominal scenario class is distinguished by the fact that it does not have an initiating event. The other three scenario classes are based on initiating events associated with a probability of occurrence. Igneous events are based on probabilities provided by DTN: LA0307BY831811.001 [DIRS 164713], file: *Pecdist-la.xls*, worksheet "Table 22." Seismic events are based on probabilities provided by DTN: MO0703PASEISDA.002 [DIRS 183156], file: *Seismic Damage Abstractions for TSPA Compliance Case.doc*. The early failure scenario class is based on probabilities of occurrences described in DTN: MO0701PASHIELD.000 [DIRS 180508], file: *Tables for DTN Readme.doc*.

These basic scenario classes are independent of each other but are not mutually exclusive. In other words, the occurrence or nonoccurrence of one scenario class has no effect on the probability of occurrence of the other scenario 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. This is graphically depicted in Figure 6-2, in which 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 early failure 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.



NOTE: The cross-hatching indicates that nominal processes occur in each scenario class.

Figure 6-2. Sets of Futures or Scenario Classes Associated with Disruptive Events: Igneous (I), Seismic (S), and Early Failure (EF) Scenario Classes

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

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.

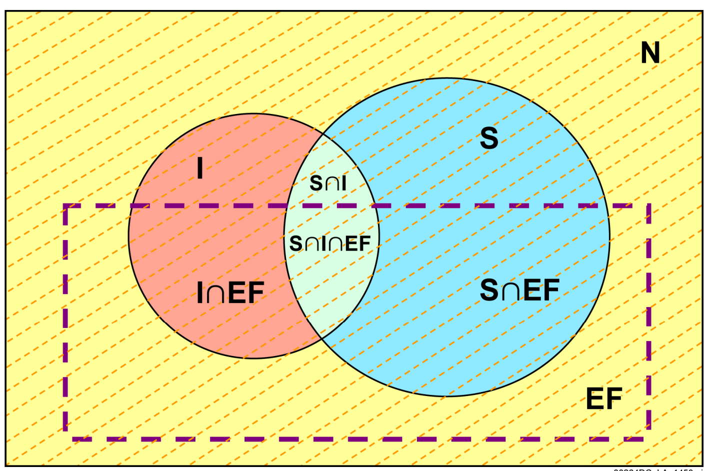
Seismic/early-failure scenario set, *S*$_{S+EF}$—The set of futures each of which includes one or more seismic events and one or more early-failure events, but no igneous events, and also includes nominal waste package and drip shield corrosion/degradation processes.

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 above scenario classes.

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. Figure 6-3 is a Venn Diagram representing the eight mutually exclusive sets. Because the union of the eight sets equals all possible futures of the repository, and the eight sets are disjoint, the probabilities associated with each of the eight sets sum to exactly one.



NOTE: The cross-hatching indicates that nominal processes occur in each scenario class.

Figure 6-3. Sets of Disjoint Scenario Classes or Subsets Associated with Igneous (I), Seismic (S), and Early-Failure (EF): Nominal (N), Seismic/Igneous (I+S), Seismic/Early Failure (S+EF), Igneous/Early Failure (I+EF), and Seismic/Igneous/Early-Failure (S+I+EF)

Note that formation of subsets of repository futures occurs 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. 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) [DIRS 178394] states:

(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) in this section for unlikely FEPs.

(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 those causing damage to the waste packages directly, causing releases of radionuclides to the biosphere, atmosphere, or ground water.

Additionally, the computational burden for the performance assessments can be unnecessarily increased by the specification of a large number of scenario classes in the TSPA. Thus, it is useful and convenient to form scenario classes with consideration of these requirements. With some additional knowledge about the probabilities of the events, an understanding of the 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, which allow these eight sets of repository futures to be further aggregated into primary scenario classes for the purposes of calculation and analyses.

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). This scenario class further consists of two cases:

- Drip Shield Early Failure
- Waste Package Early Failure.

Igneous Scenario Class, A_I—The set of futures each of which includes one or more igneous events. This class consists of two cases:

- Igneous Intrusion
- Volcanic Eruption.

Seismic Scenario Class, $\boldsymbol{A_S}$—The set of futures each of which includes one or more seismic events. This class consists of two cases:

- Seismic Ground Motion
- Seismic Fault Displacement.

Nominal Scenario Class, $\boldsymbol{A_N}$—The set of futures that include nominal features and processes (e.g., corrosion processes, such as general corrosion, localized corrosion, and stress corrosion cracking) but no disruptive events (i.e., no igneous and no seismic events and no early waste package or drip shield failures) are described below. The TSPA model calculates performance measures (e.g., mean and median annual dose) for the repository system. Performance measures calculated from each class will then be combined, with proper accounting for the probabilities of the contributing scenario classes, to calculate annual dose to the RMEI.

Another special analysis is evaluation of potential human intrusion into the repository, that will be evaluated separately from the compliance analyses described above, as required by regulation 10 CFR Part 63 [DIRS 180319]. The human intrusion evaluation is a stylized scenario specified in 10 CFR 63.321 [DIRS 178394] and 10 CFR 63.322 [DIRS 180319] that describes performance of the repository system in the event there is a single human intrusion as a result of exploratory drilling for groundwater. The probability of this event is not evaluated. Consistent with requirements in 10 CFR 63.321 [DIRS 178394], human intrusion is assumed to occur "at the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers." This evaluation is also described below. Total annual dose to the RMEI will be calculated from this evaluation directly and compared separately to the human intrusion individual protection standard.

6.3.1 Nominal Scenario Class

The nominal scenario class for the TSPA model will include all FEPs that are screened in (included) according to the FEP screening process, except for those FEPs related to early waste package and drip shield failure, igneous activity, seismic activity, or human intrusion. Those FEPs are included in the other scenario classes described below. In particular, this scenario class includes waste packages and drip shields that are subject to EBS environments and degrade with time because of corrosion processes (e.g., general corrosion or stress corrosion cracking). The nominal scenario class also incorporates the important effects and system perturbations caused by climate change and repository heating projected to occur after repository closure. If waste packages and drip shields breach and waste forms are subsequently exposed to water, radionuclides may be mobilized and eventually released from the repository. These radionuclides can then be transported by groundwater percolating through the unsaturated zone to the saturated zone and then to the accessible environment by water flowing in the saturated zone. The TSPA model includes FEPs associated with the biosphere in order to calculate annual dose to the RMEI. Therefore, the TSPA model explicitly includes the following model components:

- Unsaturated Zone Flow
- EBS Environment
- Waste Package and Drip Shield Degradation

- Waste Form Degradation and Mobilization
- EBS Flow and Transport
- Unsaturated Zone Transport
- Saturated Zone Flow and Transport
- Biosphere.

6.3.2. Early Failure Scenario Class

The early failure scenario class will include all FEPs related to early waste package and drip shield failure due to manufacturing or material defects or to preemplacement operations including improper heat treatment. In addition, this scenario class will include all FEPs that are included in the nominal scenario class. As in the nominal scenario class, if waste packages and drip shields breach and the waste forms are subsequently exposed to water, radionuclides may be mobilized and eventually released from the repository. These radionuclides can then be transported by groundwater percolating through the unsaturated zone to the saturated zone and then to the accessible environment by water flowing in the saturated zone. The TSPA model includes FEPs associated with the biosphere in order to calculate annual dose to the RMEI. Therefore, the TSPA model explicitly includes the following model components:

- Unsaturated Zone Flow
- EBS Environment
- Waste Package and Drip Shield Degradation
- Waste Form Degradation and Mobilization
- EBS Flow and Transport
- Unsaturated Zone Transport
- Saturated Zone Flow and Transport
- Biosphere.

6.3.3 Igneous Scenario Class

The igneous scenario class describes performance of the repository system in the event of igneous activity that disrupts the repository. This scenario class will include all FEPs related to igneous activity. Igneous disruption of the repository is addressed two ways: (1) igneous intrusion event represents the interaction of intrusive magma with the repository and the release of radionuclides to the groundwater, and (2) volcanic eruption event represents the eruption at the land surface and the release of radionuclides to the atmosphere.

The igneous intrusion class assumes that a dike intersects the repository and sufficiently damages drip shields and waste packages in those drifts intruded by magma and that they provide no further barrier to water flow. The magma flowing into the drifts remain in the subsurface with no eruption out of the ground surface. Prior to magma intrusion, waste packages and drip shields throughout the repository are subject to EBS environments and degrade with time because of corrosion processes (e.g., general corrosion or stress corrosion cracking)). After magma intrusion, these corrosion processes continue to act on those drip shields and waste packages located in unintruded drifts. In those waste packages that are damaged by magma or eventually breached by nominal processes, radionuclides are instantly degraded, with the exception of waste in the high-level (radioactive) waste (HLW) glass form that undergoes the same degradation process as described in the nominal scenario class. The mobilized radionuclides are eventually released from the repository. The released radionuclides may then move down through the unsaturated zone to the saturated zone, and then be transported through to the accessible environment. The TSPA model components needed to calculate total system performance for the Igneous Intrusion event include the following:

- Unsaturated Zone Flow
- EBS Environment
- Waste Package and Drip Shield Degradation
- Waste Form Degradation and Mobilization
- EBS Flow and Transport
- Unsaturated Zone Transport
- Saturated Zone Flow and Transport
- Biosphere.

Volcanic eruption events represent the fraction of igneous intrusions in which a volcanic eruption also occurs. For this class, waste remaining in those waste packages intersected by one or more eruptive conduits is transported to the land surface, and tephra and entrained waste are discharged into the atmosphere, transported by wind, and deposited on the surface. The volcanic eruption case also evaluates the fluvial and eolian redistribution of contaminated tephra deposited on the land surface. The TSPA model uses the following model components and processes to calculate repository system performance for the volcanic eruption events:

- Volcanic Interaction with the Repository
- Atmospheric Transport
- Tephra Redistribution
- Biosphere.

6.3.4 Seismic Scenario Class

The seismic scenario class describes performance of the repository system in the event of seismic activity capable of disrupting repository emplacement drifts and the EBS. This scenario class will include all FEPs that are included in the nominal scenario class. In addition, this scenario class includes damage to drip shields and waste packages as a function of the magnitude of the event. Radionuclides in breached waste packages may be mobilized and transported out of the repository, transported to the water table by the groundwater percolating through the unsaturated zone, and then transported to the accessible environment by water flowing in the saturated zone.

The seismic scenario class is addressed in two ways. Seismic ground motion represents drip shields and waste packages that fail from mechanical damage associated with seismic vibratory ground motion. Seismic fault displacement represents drip shields and waste packages that fail from mechanical damage associated with fault displacement.

Seismic classes includes general corrosion and stress corrosion cracking processes on the drip shield and waste package outer surface, localized corrosion processes on the waste packages exposed to water that flow through failed drip shields, waste package failure due to plastic rupture, and drip shield and waste package failure caused by rubble loading on the structures. In this case, mechanical damage to waste package and drip shield from ground motion is included in the waste form degradation and mobilization model component.

Seismic fault displacement includes disruption of the waste packages and drip shields by the displacement of faults as well as localized corrosion failure of waste packages exposed to water that flows through failed drip shield. These events may be considered as independent models, although the initiation of the fault displacement model occurs only for large ground motion displacements. In this case, mechanical damage to waste package and drip shield from ground motion or fault displacements is included in the waste form degradation and mobilization model component. Model components needed to calculate total system performance for the above seismic class include the following:

- Unsaturated Zone Flow
- EBS Environment
- Waste Package and Drip Shield Degradation
- Waste Form Degradation and Mobilization
- EBS Flow and Transport
- Unsaturated Zone Transport
- Saturated Zone Flow and Transport
- Biosphere.

6.3.5 Scenario Class Formation Considering the Human Intrusion Standard

This evaluation is a stylized analysis specified in 10 CFR 63.321 [DIRS 178394] and 10 CFR 63.322 [DIRS 180319] that describes performance of the repository system in the event there is a single human intrusion as a result of exploratory drilling for groundwater. The human intrusion borehole will be drilled from the ground surface, through the drip shield and a single degraded waste package, to the uppermost aquifer underlying the repository. This analysis includes: flow of water down the borehole and into the penetrated waste package, transport of radionuclides down the borehole to the water table, and transport of radionuclides through the saturated zone to the accessible environment. This analysis will include most FEPs that are included in the nominal scenario class. Exceptions are invert and EBS- unsaturated zone interface FEPs. The time of drilling intrusion is the earliest time after disposal that the waste package would degrade sufficiently that intrusion could occur without recognition by the drillers. Specifically, this time is determined to be about 230,000 years in the nominal case by analysis of general corrosion of the drip shield. The corrosion rates are found in DTN: SN0704PADSGCMT.001 [DIRS 182122], and discussion of the computation of the earliest waste package penetration time, is given in *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008 [DIRS 183478], Section 6.7.2). Model components needed to calculate total system performance for the human intrusion evaluation include the following:

- Unsaturated Zone Flow
- EBS Environments
- Waste Package and Drip Shield Degradation

- Waste Form Degradation and Mobilization
- EBS Flow and Transport
- Unsaturated Zone Transport
- Saturated Zone Flow and Transport
- Biosphere.

Furthermore, in accordance with 10 CFR 63.322(g) [DIRS 180319], human intrusion does not consider the effects of unlikely events (i.e., events with an annual exceedance probability less than 10^{-5}). The mean annual probability of an igneous event intersecting the repository is 1.7×10^{-8} (DTN: LA0307BY831811.001 [DIRS 164713], file: *Pecdist-la.xls*), which makes it an unlikely event that does not need to be considered in conjunction with human intrusion. Similarly, seismic events with annual exceedance probabilities of less than 10^{-5} are unlikely events and do not need to be considered in conjunction with human intrusion. Drip shield and waste package damage from seismic events with annual exceedance probabilities of 10^{-5} or greater corresponding to peak ground velocities of approximately 1 m/s or less (DTN: MO0501BPVELEMP.001 [DIRS 172682], file: *Bounded Horizontal Peak Ground Velocity Hazard at the Repository Waste Emplacement Level.xls*), is not significant enough to alter any material properties with respect to the potential for recognition by a driller. Therefore, there is no additional effect with respect to human intrusion screening.

7. CONCLUSIONS

The four objectives of this report were to document (a) the origin and the methods used in the development of a comprehensive list of FEPs that could potentially affect the postclosure performance of the YMP disposal system, (b) the methodology and guidance used to screen FEPs for inclusion or exclusion from the TSPA-LA analysis, (c) the methodology and guidance used to create scenario classes, and (d) compliance with the NUREG-1804 (NRC 2003 [DIRS 163274]) acceptance criteria outlined in Section 4.2.1. This section addresses the first three objectives by presenting the YMP FEP list, summarizing the screening criteria to be used in the screening process, and summarizing the scenario classes. Section 7.1 presents a discussion of the NUREG-1804 (NRC 2003 [DIRS 163274]) acceptance criteria and how these criteria are met, which satisfies the fourth objective.

Table 7-1 presents the list of FEPs to be screened in accordance with the criteria outlined in this report (Sections 4.2.2 and 6.2). As described in Section 6.1.1, there were only minor changes from the preliminary TSPA-LA FEP list (DTN: MO0508SEPFEPLA.002 [DIRS 175064]). FEP 1.2.04.04.0C (Magma and Gas Flow through Magma Bulkheads) has been deleted because this feature (magma bulkheads) was eliminated from the repository design (BSC 2006 [DIRS 180434]). Also, the name of FEP 2.3.11.02.0A has been changed from “Surface Runoff and Flooding” to “Surface Runoff and Evapotranspiration” to better represent the process described by the FEP. Other minor changes to FEP descriptions or names are explicitly identified in DTN: MO0706SPAFEPLA.001 [DIRS 181613] in Table “FEP History File” and in the “Historical_Notes” field in Table “FEPs.”

Sections 4.2.2 and 6.2 detail the regulatory screening criteria to be used to screen each YMP FEP for inclusion or exclusion from TSPA-LA analysis. To summarize, FEPs are screened by one or more of the following:

- Low consequence criteria
- Low probability criteria
- Regulatory criteria.

In addition, FEPs included in the TSPA-LA model specifically require inclusion in performance assessments conducted to demonstrate compliance with the individual protection standard (10 CFR 63.311 [DIRS 178394]), groundwater protection standard (10 CFR 63.331 [DIRS 180319]), and the individual protection standard for human intrusion (10 CFR 63.321 [DIRS 178394]). The results of this FEP screening are reported in the companion report (SNL 2008 [DIRS 183041], Section 6).

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. The scenario classes that have been identified for the TSPA-LA analysis are: igneous, seismic, nominal and early failure. These scenario classes have been identified to be representative of the range of futures that are potentially relevant to the licensing of the facility and fit into the TSPA-LA computational structure amenable for consequence analyses.

In addition, scenario class formation for a human intrusion event is necessary to address the regulatory specification used to evaluate the resilience of a geologic repository at the Yucca Mountain site. This scenario class is a stylized scenario class, meaning the processes included are specified by the regulation, instead of being based on probabilities of occurrence.

Table 7-1. Yucca Mountain Project Features, Events, and Processes List

FEP Number	FEP Name
0.1.02.00.0A	Timescales of Concern
0.1.03.00.0A	Spatial Domain of Concern
0.1.09.00.0A	Regulatory Requirements and Exclusions
0.1.10.00.0A	Model and Data Issues
1.1.01.01.0A	Open Site Investigation Boreholes
1.1.01.01.0B	Influx Through Holes Drilled in Drift Wall or Crown
1.1.02.00.0A	Chemical Effects of Excavation and Construction in EBS
1.1.02.00.0B	Mechanical Effects of Excavation and Construction in EBS
1.1.02.01.0A	Site Flooding (During Construction and Operation)
1.1.02.02.0A	Preclosure Ventilation
1.1.02.03.0A	Undesirable Materials Left
1.1.03.01.0A	Error in Waste Emplacement
1.1.03.01.0B	Error in Backfill Emplacement
1.1.04.01.0A	Incomplete Closure
1.1.05.00.0A	Records and Markers for the Repository
1.1.07.00.0A	Repository Design
1.1.08.00.0A	Inadequate Quality Control and Deviations from Design
1.1.09.00.0A	Schedule and Planning
1.1.10.00.0A	Administrative Control of the Repository Site
1.1.11.00.0A	Monitoring of the Repository
1.1.12.01.0A	Accidents and Unplanned Events During Construction and Operation
1.1.13.00.0A	Retrievability
1.2.01.01.0A	Tectonic Activity - Large Scale
1.2.02.01.0A	Fractures
1.2.02.02.0A	Faults
1.2.02.03.0A	Fault Displacement Damages EBS Components
1.2.03.02.0A	Seismic Ground Motion Damages EBS Components
1.2.03.02.0B	Seismic-Induced Rockfall 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 thermohydrology
1.2.03.02.0E	Seismic-Induced Drift Collapse Alters In-Drift Chemistry
1.2.03.03.0A	Seismicity Associated With Igneous Activity
1.2.04.02.0A	Igneous Activity Changes Rock Properties
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
1.2.04.05.0A	Magma or Pyroclastic Base Surge Transports Waste
1.2.04.06.0A	Eruptive Conduit to Surface Intersects Repository
1.2.04.07.0A	Ashfall

Table 7-1. Yucca Mountain Project Features, Events, and Processes List (Continued)

FEP Number	FEP Name
1.2.04.07.0B	Ash Redistribution in Groundwater
1.2.04.07.0C	Ash Redistribution Via Soil and Sediment Transport
1.2.05.00.0A	Metamorphism
1.2.06.00.0A	Hydrothermal Activity
1.2.07.01.0A	Erosion/Denudation
1.2.07.02.0A	Deposition
1.2.08.00.0A	Diagenesis
1.2.09.00.0A	Salt Diapirism and Dissolution
1.2.09.01.0A	Diapirism
1.2.09.02.0A	Large-Scale Dissolution
1.2.10.01.0A	Hydrologic Response to Seismic Activity
1.2.10.02.0A	Hydrologic Response to Igneous Activity
1.3.01.00.0A	Climate Change
1.3.04.00.0A	Periglacial Effects
1.3.05.00.0A	Glacial and Ice Sheet Effect
1.3.07.01.0A	Water Table Decline
1.3.07.02.0A	Water Table Rise Affects SZ
1.3.07.02.0B	Water Table Rise Affects UZ
1.4.01.00.0A	Human Influences on Climate
1.4.01.01.0A	Climate Modification Increases Recharge
1.4.01.02.0A	Greenhouse Gas Effects
1.4.01.03.0A	Acid Rain
1.4.01.04.0A	Ozone Layer Failure
1.4.02.01.0A	Deliberate Human Intrusion
1.4.02.02.0A	Inadvertent Human Intrusion
1.4.02.03.0A	Igneous Event Precedes Human Intrusion
1.4.02.04.0A	Seismic Event Precedes Human Intrusion
1.4.03.00.0A	Unintrusive Site Investigation
1.4.04.00.0A	Drilling Activities (Human Intrusion)
1.4.04.01.0A	Effects of Drilling Intrusion
1.4.05.00.0A	Mining and Other Underground Activities (Human Intrusion)
1.4.06.01.0A	Altered Soil or Surface Water Chemistry
1.4.07.01.0A	Water Management Activities
1.4.07.02.0A	Wells
1.4.07.03.0A	Recycling of Accumulated Radionuclides from Soils to Groundwater
1.4.08.00.0A	Social and Institutional Developments
1.4.09.00.0A	Technological Developments
1.4.11.00.0A	Explosions and Crashes (Human Activities)
1.5.01.01.0A	Meteorite Impact
1.5.01.02.0A	Extraterrestrial Events
1.5.02.00.0A	Species Evolution
1.5.03.01.0A	Changes in the Earth's Magnetic Field
1.5.03.02.0A	Earth Tides
2.1.01.01.0A	Waste Inventory

Table 7-1. Yucca Mountain Project Features, Events, and Processes List (Continued)

FEP Number	FEP Name
2.1.01.02.0A	Interactions Between Co-Located Waste
2.1.01.02.0B	Interactions Between Co-Disposed Waste
2.1.01.03.0A	Heterogeneity of Waste Inventory
2.1.01.04.0A	Repository-Scale Spatial Heterogeneity of Emplaced Waste
2.1.02.01.0A	DSNF Degradation (Alteration, Dissolution, and Radionuclide Release)
2.1.02.02.0A	CSNF Degradation (Alteration, Dissolution, and Radionuclide Release)
2.1.02.03.0A	HLW Glass Degradation (Alteration, Dissolution, and Radionuclide Release)
2.1.02.04.0A	Alpha Recoil Enhances Dissolution
2.1.02.05.0A	HLW Glass Cracking
2.1.02.06.0A	HLW Glass Recrystallization
2.1.02.07.0A	Radionuclide Release from Gap and Grain Boundaries
2.1.02.08.0A	Pyrophoricity from DSNF
2.1.02.09.0A	Chemical Effects of Void Space in Waste Package
2.1.02.10.0A	Organic/Cellulosic Materials in Waste
2.1.02.11.0A	Degradation of Cladding from Waterlogged Rods
2.1.02.12.0A	Degradation of Cladding Prior To Disposal
2.1.02.13.0A	General Corrosion of Cladding
2.1.02.14.0A	Microbially Influenced Corrosion (MIC) of Cladding
2.1.02.15.0A	Localized (Radiolysis Enhanced) Corrosion of Cladding
2.1.02.16.0A	Localized (Pitting) Corrosion of Cladding
2.1.02.17.0A	Localized (Crevice) Corrosion of Cladding
2.1.02.18.0A	Enhanced Corrosion of Cladding from Dissolved Silica
2.1.02.19.0A	Creep Rupture of Cladding
2.1.02.20.0A	Internal Pressurization of Cladding
2.1.02.21.0A	Stress Corrosion Cracking (SCC) of Cladding
2.1.02.22.0A	Hydride Cracking of Cladding
2.1.02.23.0A	Cladding Unzipping
2.1.02.24.0A	Mechanical Impact on Cladding
2.1.02.25.0A	DSNF Cladding
2.1.02.25.0B	Naval SNF Cladding
2.1.02.26.0A	Diffusion-Controlled Cavity Growth in Cladding
2.1.02.27.0A	Localized (Fluoride Enhanced) Corrosion of Cladding
2.1.02.28.0A	Grouping of DSNF Waste Types into Categories
2.1.02.29.0A	Flammable Gas Generation from DSNF
2.1.03.01.0A	General Corrosion of Waste Packages
2.1.03.01.0B	General Corrosion of Drip Shields
2.1.03.02.0A	Stress Corrosion Cracking (SCC) of Waste Packages
2.1.03.02.0B	Stress Corrosion Cracking (SCC) of Drip Shields
2.1.03.03.0A	Localized Corrosion of Waste Packages
2.1.03.03.0B	Localized Corrosion of Drip Shields
2.1.03.04.0A	Hydride Cracking of Waste Packages
2.1.03.04.0B	Hydride Cracking of Drip Shields
2.1.03.05.0A	Microbially Influenced Corrosion (MIC) of Waste Packages
2.1.03.05.0B	Microbially Influenced Corrosion (MIC) of Drip Shields

Table 7-1. Yucca Mountain Project Features, Events, and Processes List (Continued)

FEP Number	FEP Name
2.1.03.06.0A	Internal Corrosion of Waste Packages Prior To Breach
2.1.03.07.0A	Mechanical Impact on Waste Package
2.1.03.07.0B	Mechanical Impact on Drip Shield
2.1.03.08.0A	Early Failure of Waste Packages
2.1.03.08.0B	Early Failure of Drip Shields
2.1.03.09.0A	Copper Corrosion in EBS
2.1.03.10.0A	Advection of Liquids and Solids Through Cracks in the Waste Package
2.1.03.10.0B	Advection of Liquids and Solids Through Cracks in the Drip Shield
2.1.03.11.0A	Physical Form of Waste Package and Drip Shield
2.1.04.01.0A	Flow in the Backfill
2.1.04.02.0A	Chemical Properties and Evolution of Backfill
2.1.04.03.0A	Erosion or Dissolution of Backfill
2.1.04.04.0A	Thermal-Mechanical Effects of Backfill
2.1.04.05.0A	Thermal-Mechanical Properties and Evolution of Backfill
2.1.04.09.0A	Radionuclide Transport in Backfill
2.1.05.01.0A	Flow Through Seals (Access Ramps and Ventilation Shafts)
2.1.05.02.0A	Radionuclide Transport Through Seals
2.1.05.03.0A	Degradation of Seals
2.1.06.01.0A	Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS
2.1.06.02.0A	Mechanical Effects of Rock Reinforcement Materials in EBS
2.1.06.04.0A	Flow Through Rock Reinforcement Materials in EBS
2.1.06.05.0A	Mechanical Degradation of Emplacement Pallet
2.1.06.05.0B	Mechanical Degradation of Invert
2.1.06.05.0C	Chemical Degradation of Emplacement Pallet
2.1.06.05.0D	Chemical Degradation of Invert
2.1.06.06.0A	Effects of Drip Shield on Flow
2.1.06.06.0B	Oxygen Embrittlement of Drip Shields
2.1.06.07.0A	Chemical Effects at EBS Component Interfaces
2.1.06.07.0B	Mechanical Effects at EBS Component Interfaces
2.1.07.01.0A	Rockfall
2.1.07.02.0A	Drift Collapse
2.1.07.04.0A	Hydrostatic Pressure on Waste Package
2.1.07.04.0B	Hydrostatic Pressure on Drip Shield
2.1.07.05.0A	Creep of Metallic Materials in the Waste Package
2.1.07.05.0B	Creep of Metallic Materials in the Drip Shield
2.1.07.06.0A	Floor Buckling
2.1.08.01.0A	Water Influx at the Repository
2.1.08.01.0B	Effects of Rapid Influx Into the Repository
2.1.08.02.0A	Enhanced Influx at the Repository
2.1.08.03.0A	Repository Dry-Out Due to Waste Heat
2.1.08.04.0A	Condensation Forms on Roofs of Drifts (Drift-Scale Cold Traps)
2.1.08.04.0B	Condensation Forms at Repository Edges (Repository-Scale Cold Traps)
2.1.08.05.0A	Flow Through Invert
2.1.08.06.0A	Capillary Effects (Wicking) in EBS

Table 7-1. Yucca Mountain Project Features, Events, and Processes List (Continued)

FEP Number	FEP Name
2.1.08.07.0A	Unsaturated Flow in the EBS
2.1.08.09.0A	Saturated Flow in the EBS
2.1.08.11.0A	Repository Resaturation Due to Waste Cooling
2.1.08.12.0A	Induced Hydrologic Changes in Invert
2.1.08.14.0A	Condensation On Underside of Drip Shield
2.1.08.15.0A	Consolidation of EBS Components
2.1.09.01.0A	Chemical Characteristics of Water in Drifts
2.1.09.01.0B	Chemical Characteristics of Water in Waste Package
2.1.09.02.0A	Chemical Interaction with Corrosion Products
2.1.09.03.0A	Volume Increase of Corrosion Products Impacts Cladding
2.1.09.03.0B	Volume Increase of Corrosion Products Impacts Waste Package
2.1.09.03.0C	Volume Increase of Corrosion Products Impacts Other EBS Components
2.1.09.04.0A	Radionuclide Solubility, Solubility Limits, and Speciation in the Waste Form and EBS
2.1.09.05.0A	Sorption of Dissolved Radionuclides in EBS
2.1.09.06.0A	Reduction-Oxidation Potential in Waste Package
2.1.09.06.0B	Reduction-Oxidation Potential in Drifts
2.1.09.07.0A	Reaction Kinetics in Waste Package
2.1.09.07.0B	Reaction Kinetics in Drifts
2.1.09.08.0A	Diffusion of Dissolved Radionuclides in EBS
2.1.09.08.0B	Advection of Dissolved Radionuclides in EBS
2.1.09.09.0A	Electrochemical Effects in EBS
2.1.09.10.0A	Secondary Phase Effects on Dissolved Radionuclide Concentrations
2.1.09.11.0A	Chemical Effects of Waste-Rock Contact
2.1.09.12.0A	Rind (Chemically Altered Zone) Forms in the Near-Field
2.1.09.13.0A	Complexation in EBS
2.1.09.15.0A	Formation of True (Intrinsic) Colloids in EBS
2.1.09.16.0A	Formation of Pseudo-Colloids (Natural) in EBS
2.1.09.17.0A	Formation of Pseudo-Colloids (Corrosion Product) in EBS
2.1.09.18.0A	Formation of Microbial Colloids in EBS
2.1.09.19.0A	Sorption of Colloids in EBS
2.1.09.19.0B	Advection of Colloids in EBS
2.1.09.20.0A	Filtration of Colloids in EBS
2.1.09.21.0A	Transport of Particles Larger Than Colloids in EBS
2.1.09.21.0B	Transport of Particles Larger Than Colloids in the SZ
2.1.09.21.0C	Transport of Particles Larger Than Colloids in the UZ
2.1.09.22.0A	Sorption of Colloids At Air-Water Interface
2.1.09.23.0A	Stability of Colloids in EBS
2.1.09.24.0A	Diffusion of Colloids in EBS
2.1.09.25.0A	Formation of Colloids (Waste-Form) By Co-Precipitation in EBS
2.1.09.26.0A	Gravitational Settling of Colloids in EBS
2.1.09.27.0A	Coupled Effects On Radionuclide Transport in EBS
2.1.09.28.0A	Localized Corrosion On Waste Package Outer Surface Due to Deliquescence
2.1.09.28.0B	Localized Corrosion On Drip Shield Surfaces Due to Deliquescence

Table 7-1. Yucca Mountain Project Features, Events, and Processes List (Continued)

FEP Number	FEP Name
2.1.10.01.0A	Microbial Activity in EBS
2.1.11.01.0A	Heat Generation in EBS
2.1.11.02.0A	Non-Uniform Heat Distribution in EBS
2.1.11.03.0A	Exothermic Reactions in the EBS
2.1.11.05.0A	Thermal Expansion/Stress of In-Package EBS Components
2.1.11.06.0A	Thermal Sensitization of Waste Packages
2.1.11.06.0B	Thermal Sensitization of Drip Shields
2.1.11.07.0A	Thermal Expansion/Stress of In-Drift EBS Components
2.1.11.08.0A	Thermal Effects on Chemistry and Microbial Activity in the EBS
2.1.11.09.0A	Thermal Effects on Flow in the EBS
2.1.11.09.0B	Thermally-Driven Flow (Convection) in Waste Packages
2.1.11.09.0C	Thermally Driven Flow (Convection) in Drifts
2.1.11.10.0A	Thermal Effects on Transport in EBS
2.1.12.01.0A	Gas Generation (Repository Pressurization)
2.1.12.02.0A	Gas Generation (He) from Waste Form Decay
2.1.12.03.0A	Gas Generation (H2) from Waste Package Corrosion
2.1.12.04.0A	Gas Generation (CO2, CH4, H2S) from Microbial Degradation
2.1.12.06.0A	Gas Transport in EBS
2.1.12.07.0A	Effects of Radioactive Gases in EBS
2.1.12.08.0A	Gas Explosions in EBS
2.1.13.01.0A	Radiolysis
2.1.13.02.0A	Radiation Damage in EBS
2.1.13.03.0A	Radiological Mutation of Microbes
2.1.14.15.0A	In-Package Criticality (Intact Configuration)
2.1.14.16.0A	In-Package Criticality (Degraded Configurations)
2.1.14.17.0A	Near-Field Criticality
2.1.14.18.0A	In-Package Criticality Resulting from a Seismic Event (Intact Configuration)
2.1.14.19.0A	In-Package Criticality Resulting from a Seismic Event (Degraded Configurations)
2.1.14.20.0A	Near-Field Criticality Resulting from a Seismic Event
2.1.14.21.0A	In-Package Criticality Resulting from Rockfall (Intact Configuration)
2.1.14.22.0A	In-Package Criticality Resulting from Rockfall (Degraded Configurations)
2.1.14.23.0A	Near-Field Criticality Resulting from Rockfall
2.1.14.24.0A	In-Package Criticality Resulting from an Igneous Event (Intact Configuration)
2.1.14.25.0A	In-Package Criticality Resulting from an Igneous Event (Degraded Configurations)
2.1.14.26.0A	Near-Field Criticality Resulting from an Igneous Event
2.2.01.01.0A	Mechanical Effects of Excavation and Construction in the Near-Field
2.2.01.01.0B	Chemical Effects of Excavation and Construction in the Near-Field
2.2.01.02.0A	Thermally-Induced Stress Changes in the Near-Field
2.2.01.02.0B	Chemical Changes in the Near-Field from Backfill
2.2.01.03.0A	Changes In Fluid Saturations in the Excavation Disturbed Zone
2.2.01.04.0A	Radionuclide Solubility in the Excavation Disturbed Zone
2.2.01.05.0A	Radionuclide Transport in the Excavation Disturbed Zone
2.2.03.01.0A	Stratigraphy
2.2.03.02.0A	Rock Properties of Host Rock and Other Units

Table 7-1. Yucca Mountain Project Features, Events, and Processes List (Continued)

FEP Number	FEP Name
2.2.06.01.0A	Seismic Activity Changes Porosity and Permeability of Rock
2.2.06.02.0A	Seismic Activity Changes Porosity and Permeability of Faults
2.2.06.02.0B	Seismic Activity Changes Porosity and Permeability of Fractures
2.2.06.03.0A	Seismic Activity Alters Perched Water Zones
2.2.06.04.0A	Effects of Subsidence
2.2.06.05.0A	Salt Creep
2.2.07.01.0A	Locally Saturated Flow At Bedrock/Alluvium Contact
2.2.07.02.0A	Unsaturated Groundwater Flow in the Geosphere
2.2.07.03.0A	Capillary Rise in the UZ
2.2.07.04.0A	Focusing of Unsaturated Flow (Fingers, Weeps)
2.2.07.05.0A	Flow in the UZ from Episodic Infiltration
2.2.07.06.0A	Episodic or Pulse Release from Repository
2.2.07.06.0B	Long-Term Release of Radionuclides from the Repository
2.2.07.07.0A	Perched Water Develops
2.2.07.08.0A	Fracture Flow in the UZ
2.2.07.09.0A	Matrix Imbibition in the UZ
2.2.07.10.0A	Condensation Zone Forms Around Drifts
2.2.07.11.0A	Resaturation of Geosphere Dry-Out Zone
2.2.07.12.0A	Saturated Groundwater Flow in the Geosphere
2.2.07.13.0A	Water-Conducting Features in the SZ
2.2.07.14.0A	Chemically-Induced Density Effects On Groundwater Flow
2.2.07.15.0A	Advection and Dispersion in the SZ
2.2.07.15.0B	Advection and Dispersion in the UZ
2.2.07.16.0A	Dilution of Radionuclides in Groundwater
2.2.07.17.0A	Diffusion in the SZ
2.2.07.18.0A	Film Flow Into the Repository
2.2.07.19.0A	Lateral Flow from Solitario Canyon Fault Enters Drifts
2.2.07.20.0A	Flow Diversion Around Repository Drifts
2.2.07.21.0A	Drift Shadow Forms Below Repository
2.2.08.01.0A	Chemical Characteristics of Groundwater in the SZ
2.2.08.01.0B	Chemical Characteristics of Groundwater in the UZ
2.2.08.03.0A	Geochemical Interactions and Evolution in the SZ
2.2.08.03.0B	Geochemical Interactions and Evolution in the UZ
2.2.08.04.0A	Re-Dissolution of Precipitates Directs More Corrosive Fluids to Waste Packages
2.2.08.05.0A	Diffusion in the UZ
2.2.08.06.0A	Complexation in the SZ
2.2.08.06.0B	Complexation in the UZ
2.2.08.07.0A	Radionuclide Solubility Limits in the SZ
2.2.08.07.0B	Radionuclide Solubility Limits in the UZ
2.2.08.07.0C	Radionuclide Solubility Limits in the Biosphere
2.2.08.08.0A	Matrix Diffusion in the SZ
2.2.08.08.0B	Matrix Diffusion in the UZ
2.2.08.09.0A	Sorption in the SZ
2.2.08.09.0B	Sorption in the UZ

Table 7-1. Yucca Mountain Project Features, Events, and Processes List (Continued)

FEP Number	FEP Name
2.2.08.10.0A	Colloidal Transport in the SZ
2.2.08.10.0B	Colloidal Transport in the UZ
2.2.08.11.0A	Groundwater Discharge To Surface Within the Reference Biosphere
2.2.08.12.0A	Chemistry of Water Flowing Into the Drift
2.2.08.12.0B	Chemistry of Water Flowing Into the Waste Package
2.2.09.01.0A	Microbial Activity in the SZ
2.2.09.01.0B	Microbial Activity in the UZ
2.2.10.01.0A	Repository-Induced Thermal Effects on Flow in the UZ
2.2.10.02.0A	Thermal Convection Cell Develops In SZ
2.2.10.03.0A	Natural Geothermal Effects on Flow in the SZ
2.2.10.03.0B	Natural Geothermal Effects on Flow in the UZ
2.2.10.04.0A	Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository
2.2.10.04.0B	Thermo-Mechanical Stresses Alter Characteristics of Faults Near Repository
2.2.10.05.0A	Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below the Repository
2.2.10.06.0A	Thermo-Chemical Alteration in the UZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)
2.2.10.07.0A	Thermo-Chemical Alteration of the Calico Hills Unit
2.2.10.08.0A	Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)
2.2.10.09.0A	Thermo-Chemical Alteration of the Topopah Spring Basal Vitrophyre
2.2.10.10.0A	Two-Phase Buoyant Flow/Heat Pipes
2.2.10.11.0A	Natural Air Flow in the UZ
2.2.10.12.0A	Geosphere Dry-Out Due to Waste Heat
2.2.10.13.0A	Repository-Induced Thermal Effects on Flow in the SZ
2.2.10.14.0A	Mineralogic Dehydration Reactions
2.2.11.01.0A	Gas Effects in the SZ
2.2.11.02.0A	Gas Effects in the UZ
2.2.11.03.0A	Gas Transport In Geosphere
2.2.12.00.0A	Undetected Features in the UZ
2.2.12.00.0B	Undetected Features in the SZ
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
2.2.14.12.0A	Far-Field Criticality Resulting from an Igneous Event
2.3.01.00.0A	Topography and Morphology
2.3.02.01.0A	Soil Type
2.3.02.02.0A	Radionuclide Accumulation in Soils
2.3.02.03.0A	Soil and Sediment Transport in the Biosphere
2.3.04.01.0A	Surface Water Transport and Mixing
2.3.06.00.0A	Marine Features
2.3.09.01.0A	Animal Burrowing/Intrusion
2.3.11.01.0A	Precipitation
2.3.11.02.0A	Surface Runoff and Evapotranspiration
2.3.11.03.0A	Infiltration and Recharge

Table 7-1. Yucca Mountain Project Features, Events, and Processes List (Continued)

FEP Number	FEP Name
2.3.11.04.0A	Groundwater Discharge to Surface Outside the Reference Biosphere
2.3.13.01.0A	Biosphere Characteristics
2.3.13.02.0A	Radionuclide Alteration During Biosphere Transport
2.3.13.03.0A	Effects of Repository Heat on the Biosphere
2.3.13.04.0A	Radionuclide Release Outside the Reference Biosphere
2.4.01.00.0A	Human Characteristics (Physiology, Metabolism)
2.4.04.01.0A	Human Lifestyle
2.4.07.00.0A	Dwellings
2.4.08.00.0A	Wild and Natural Land and Water Use
2.4.09.01.0A	Implementation of New Agricultural Practices or Land Use
2.4.09.01.0B	Agricultural Land Use and Irrigation
2.4.09.02.0A	Animal Farms and Fisheries
2.4.10.00.0A	Urban and Industrial Land and Water Use
3.1.01.01.0A	Radioactive Decay and InGrowth
3.2.07.01.0A	Isotopic Dilution
3.2.10.00.0A	Atmospheric Transport of Contaminants
3.3.01.00.0A	Contaminated Drinking Water, Foodstuffs and Drugs
3.3.02.01.0A	Plant Uptake
3.3.02.02.0A	Animal Uptake
3.3.02.03.0A	Fish Uptake
3.3.03.01.0A	Contaminated Non-Food Products and Exposure
3.3.04.01.0A	Ingestion
3.3.04.02.0A	Inhalation
3.3.04.03.0A	External Exposure
3.3.05.01.0A	Radiation Doses
3.3.06.00.0A	Radiological Toxicity and Effects
3.3.06.01.0A	Repository Excavation
3.3.06.02.0A	Sensitization to Radiation
3.3.07.00.0A	Non-radiological toxicity and effects
3.3.08.00.0A	Radon and radon decay product exposure

Source: DTN MO0508SEPFEPLA.002 [DIRS 175064], Table “FEPs” as modified by Section 6.1.1

7.1 RELEVANT ACCEPTANCE CRITERIA

The following acceptance criteria from NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3) identified previously in Section 4.2.2, were addressed:

NUREG-1804 Section 2.2.1.2.1.3 Acceptance Criterion 1—The Identification of a List of Features, Events, and Processes is Adequate

(1) The Safety Analysis Report contains a complete list of features, events, and processes, related to the geologic setting or the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers), that have the potential to influence repository

performance. The list is consistent with the site characterization data. Moreover, the comprehensive features, events, and processes list includes, but is not limited to, potentially disruptive events related to igneous activity (extrusive and intrusive); seismic shaking (high-frequency-low magnitude, and rare large-magnitude events); tectonic evolution (slip on existing faults and formation of new faults); climatic change (change to pluvial conditions); and criticality.

How Demonstrated

Sections 6 and 6.1 summarize YMP FEP identification and classification. As described in BSC (2005 [DIRS 173800], Section 7.2), the FEP list was initially developed from, and therefore, contains the following:

- A comprehensive set of general issues from radioactive waste disposal programs in several other countries. As noted in NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.2, Review Method 1), "available generic lists of features, events, and processes" may be used "as a reference to determine the completeness" of the FEP list. The TSPA-LA FEP list derives specifically from a comprehensive list of FEPs from other radioactive waste disposal programs (NEA International FEP Database, Version 1.0 (Safety Assessment Management (SAM) 1997 [DIRS 139333]). The NEA International FEP Database represents the best available compilation of generic FEPs.

- A set of YMP-specific issues, developed from documents that identify issues unique to the YMP design and setting (unsaturated fractured tuff). These documents include project literature addressing site characterization, igneous, seismic, and tectonic activity, climate change, and criticality.

The completeness of the initial FEP list was augmented with iterative FEP identification, classification, screening, and review cycles (see Section 6.1.1 and 6.2). Confidence can be gained through a combination of formal and systematic reviews cycles, comparisons with other FEP lists, and through the application of more than one classification scheme. The development of the TSPA-LA FEP list combined the use of all four of the most common FEP identification methods and multiple classification schemes to increase confidence in the comprehensiveness of the list. Audits performed against an alternate independent YMP FEP list (BSC 2005 [DIRS 173800], Appendix B) and against recently published international FEP lists were also performed, and no new FEPs were identified.

Continual reviews by subject matter experts, licensing and performance assessment team members, external reviewers, and others further augmented completeness. As the FEP list evolved, fewer new potential FEPs were identified during each successive review cycle (BSC 2005 [DIRS 173800], Appendix C). Over time, the nature of those potential FEPs also changed, so that they were predominantly variants or finer details of existing FEPs, rather than new unique issues.

Finally, as discussed in Section 6.1.3, the use of the FEP matrix classification (Table 6-1) provides additional confidence in the comprehensiveness of the FEP list.

NUREG-1804, Section 2.2.1.2.1.3 Acceptance Criterion 3—Formation of Scenario Classes Using the Reduced Set of Events Is Adequate

> *(1) Scenario classes are mutually exclusive and complete, clearly documented, and technically acceptable.*

How Demonstrated

Section 6.3 discusses YMP scenario class formation and satisfies part of the criterion stated above. Scenario classes identified from past FEP analysis iterations have been carried over to the current analysis. The scenario classes were formed from earlier FEP screening using the preliminary TSPA-LA included FEPs. The remaining portion of this acceptance criterion will be satisfied when the FEPs have undergone the current screening process and analysis.

For TSPA-LA, there will be a nominal scenario class, two disruptive event scenario classes (igneous and seismic), and an early failure scenario class. These scenario classes were formed based on the preliminary screened-in TSPA-LA FEPs. All included FEPs will be captured in at least one scenario class. The nominal scenario class will contain included FEPs that are expected to occur after closure (i.e., FEPs that have a probability of occurrence near 1.0, but that may have uncertain consequences). The nominal scenario class represents the most plausible evolution of the repository system and includes both favorable future conditions and potentially adverse future conditions. The nominal scenario class does not consider the occurrence of early failures, igneous or seismic events.

The disruptive event scenario classes (igneous and seismic) will contain combinations of included FEPs that have a low probability of occurrence (but greater than the screening probability criteria of one chance in 10,000 of occurring over 10,000 years) but might produce potentially adverse future conditions (i.e., radiological exposures or radionuclide releases would be significantly changed by their omission). The disruptive event scenario classes will also contain many of the nominal FEPs and represent low-probability perturbations to the expected evolution of the repository system. The igneous scenario class represents igneous intrusion and volcanic eruption events. The seismic scenario class represents vibratory ground motion and fault displacement events.

The early failure scenario class represents future performance of the repository system in the event of early failure of waste packages and drip shields. 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.

8. INPUTS AND REFERENCES

8.1 DOCUMENTS CITED

100956 Andersson, J.; Carlsson, T.; Eng, T.; Kautsky, F.; Soderman, E.; and Wingefors, S. 1989. *The Joint SKI/SKB Scenario Development Project*. Andersson, J., ed. SKB TR-89-35. Stockholm, Sweden: Svensk Kärnbränsleförsörjning A.B. TIC: 208568.

170019 BSC (Bechtel SAIC Company) 2004. *Clad Degradation – FEPs Screening Arguments*. ANL-WIS-MD-000008 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: SOC.20041020.0014; DOC.20060213.0007.

170021 BSC 2004. *Features, Events, and Processes: System Level*. ANL-WIS-MD-000019 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041020.0009; DOC.200512060019.

170020 BSC 2004. *Waste Form Features, Events, and Processes*. ANL-WIS-MD-000009 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041028.0006; DOC.20050214.0004.

168556 BSC 2004. *Screening Analysis for Criticality Features, Events, and Processes for License Application*. ANL-EBS-NU-000008 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041022.0001.

175014 BSC 2005. *Engineered Barrier System Features, Events, and Processes*. ANL-WIS-PA-000002 REV 05. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050829.0003; DOC.20050830.0006.

174107 BSC 2005. *Evaluation of Features, Events, and Processes (FEP) for the Biosphere Model*. ANL-MGR-MD-000011 REV 05. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050718.0006.

174190 BSC 2005. *Features, Events, and Processes in SZ Flow and Transport*. ANL-NBS-MD-000002 REV 04. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050822.0012.

174191 BSC 2005. *Features, Events, and Processes in UZ Flow and Transport*. ANL-NBS-MD-000001 REV 04. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050809.0002.

173981 BSC 2005. *Features, Events, and Processes: Disruptive Events*. ANL-WIS-MD-000005 REV 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050830.0008.

174995 BSC 2005. *Screening of Features, Events, and Processes in Drip Shield and Waste Package Degradation*. ANL-EBS-PA-000002 REV 05. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050817.0003; DOC.20050826.0002; DOC.20050929.0007.

173800 BSC 2005. *The Development of the Total System Performance Assessment-License Application Features, Events, and Processes*. TDR-WIS-MD-000003 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050829.0004.

180434 BSC 2006. *TMRB Decision Proposal, Remove the Requirement for Design and Installation of Magma Bulkheads in the Subsurface Repository*. TMRB-2006-018. Las Vegas, Nevada: Bechtel SAIC Company. ACC: LLR.20070323.0005.

100970 Chapman, N.A.; Andersson, J.; Robinson, P.; Skagius, K.; Wene, C-O.; Wiborgh, M.; and Wingefors, S. 1995. *Systems Analysis, Scenario Construction and Consequence Analysis Definition for SITE-94.* SKI Report 95:26. Stockholm, Sweden: Swedish Nuclear Power Inspectorate. TIC: 238888.

100975 DOE (U.S. Department of Energy) 1996. *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant*. DOE/CAO-1996-2184. Twenty-one volumes. Carlsbad, New Mexico: U.S. Department of Energy, Carlsbad Area Office. TIC: 240511.

154365 Freeze, G.A.; Brodsky, N.S.; and Swift, P.N. 2001. *The Development of Information Catalogued in REV00 of the YMP FEP Database.* TDR-WIS-MD-000003 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010301.0237.

100983 Goodwin, B.W.; Stephens, M.E.; Davison, C.C.; Johnson, L.H.; and Zach, R. 1994. *Scenario Analysis for the Postclosure Assessment of the Canadian Concept for Nuclear Fuel Waste Disposal*. AECL-10969. Pinawa, Manitoba, Canada: AECL Research, Whiteshell Laboratories. TIC: 215123.

100996 Miller, W.M. and Chapman, N.A. 1993. *HMIP Assessment of Nirex Proposals, Identification of Relevant Processes (System Concept Group Report).* Technical Report IZ3185-TR1 (Edition 1). [London], United Kingdom: Her Majesty's Inspectorate of Pollution (HMIP), Department of the Environment. TIC: 238458.

124260 NAGRA (Nationale Genossenschaft fur die Lagerung Radioaktiver Abfalle) 1994. *Kristallin-I Safety Assessment Report*. NAGRA Technical Report 93-22. Wettingen, Switzerland: National Cooperative for the Disposal of Radioactive Waste. TIC: 235964.

169902 NEA (Nuclear Energy Agency) 1999. *Nirex Methodology for Scenario and Conceptual Model Development, an International Peer Review*. Paris, France: Organization for the Economic Co-Operation and Development, Nuclear Energy Agency. TIC: 256158.

152309 NEA 1999. *An International Database of Features, Events, and Processes*. Paris, France: Organization for Economic Co-operation and Development. TIC: 248820.

163274 NRC (U.S. Nuclear Regulatory Commission) 2003. *Yucca Mountain Review Plan, Final Report.* NUREG-1804, Rev. 2. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. TIC: 254568.

100479 Nuclear Energy Agency 1992. *Systematic Approaches to Scenario Development: A Report of the NEA Working Group on Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal*. Paris, France: Nuclear Energy Agency, Organization for Economic Co-operation and Development. TIC: 8083.

139333 SAM (Safety Assessment Management) 1997. Safety Assessment of Radioactive Waste Repositories, An International Database of Features, Events, and Processes. Unpublished Draft, June 24, 1997. ACC: MOL.19991213.0522.

184327 SNL (Sandia National Laboratories) 2007. *Technical Work Plan for the Performance Assessment Features, Events, and Processes.* TWP-MGR-MD-000036 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20071207.0001.

177464 SNL 2008. *Postclosure Nuclear Safety Design Bases.* ANL-WIS-MD-000024 REV 01. Las Vegas, Nevada: Sandia National Laboratories.

173869 SNL 2008. *Screening Analysis of Criticality Features, Events, and Processes for License Application*. ANL-DS0-NU-000001 REV 00. Las Vegas, Nevada: Sandia National Laboratories.

183041 SNL 2008. *Features, Events, and Processes for the Total System Performance Assessment: Analyses.* ANL-WIS-MD-000027 REV 00. Las Vegas, Nevada: Sandia National Laboratories.

183478 SNL 2008. *Total System Performance Assessment Model /Analysis for the License Application*. MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories.

8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

180319 10 CFR 63. 2007. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Internet Accessible.

155216 66 FR 32074. 40 CFR Part 197, Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV; Final Rule. ACC: MOL.20050418.0113.

156671 66 FR 55732. Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, NV, Final Rule. 10 CFR Parts 2, 19, 20, 21, 30, 40, 51, 60, 61, 63, 70, 72, 73, and 75. ACC: MOL.20050324.0102; MOL.20050418.0124.

178394 70 FR 53313. Implementation of a Dose Standard After 10,000 Years. Internet Accessible.

IM-PRO-003, *Software Management*.

SCI-PRO-004, *Managing Technical Product Inputs*.

SCI-PRO-005, *Scientific Analyses and Calculations*.

8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

164713 LA0307BY831811.001. Characterize Igneous Framework Additional Output. Submittal date: 07/29/2003.

172682 MO0501BPVELEMP.001. Bounded Horizontal Peak Ground Velocity Hazard at the Repository Waste Emplacement Level. Submittal Date: 01/11/2005.

175064 MO0508SEPFEPLA.002. LA FEP List and Screening. Submittal date: 08/22/2005.

180508 MO0701PASHIELD.000. Waste Package/Drip Shield Early Failure Probabilities. Submittal date: 04/24/2007.

183156 MO0703PASEISDA.002. Seismic Damage Abstractions for TSPA Compliance Case. Submittal date: 09/21/2007.

181613 MO0706SPAFEPLA.001. FY 2007 LA FEP List and Screening. Submittal date: 06/20/2007.

182122 SN0704PADSGCMT.001 Drip Shield General Corrosion Models Based on 2.5-Year Titanium Grade 7 Corrosion Rates. Submittal date: 07/24/2007.

APPENDIX A
GLOSSARY

APPENDIX A – GLOSSARY

Disruptive Event Scenario Classes (Igneous and Seismic)—A scenario class that contains low probability perturbations to be expected during the evolution of the repository system. It contains one or more disruptive FEPs.

Disruptive FEP—An included FEP that depends upon an igneous or seismic event that has a probability of occurrence during the period of performance less than 1.0 (but greater than the cutoff of $10^{-4}/10^{4}$ year).

Early Failure Scenario Class—A scenario class consisting of a set of FEPs that represent a 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).

Early Failure—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.

Event Class—All possible specific initiating events that are caused by a common natural process (e.g., the event class for seismicity includes the range of possible earthquakes for the Yucca Mountain site).

Event—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 to the period of performance.

Excluded FEP—A FEP that is identified by the FEP screening process as not requiring analysis in the quantitative TSPA based on specific criteria provided by the regulation.

Feature—An object, structure, or condition that has a potential to affect disposal system performance.

FEP—A feature, event, and/or process.

Igneous Scenario Class—A scenario class consisting of FEPs that represent a 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.

Included FEP—A FEP that is identified by the FEP screening process as requiring analysis in the quantitative TSPA. All FEPs are considered included until screened as excluded per regulations (Section 4.2.2.1).

Likely FEP—A FEP that has at least one chance in 10 of occurring within 10,000 years of disposal, as per 10 CFR 63.114 [DIRS 180319].

Nominal Scenario Class—The scenario class that represents the most plausible evolution of the repository system during the first 10,000 years and includes both favorable future conditions and potentially adverse future conditions. It contains no disruptive FEPs. Note that the nominal scenario class is not the most plausible class over the period from postclosure until the period of geologic stability.

Period of Geologic Stability—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.

Process—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.

Scenario Class—A set of scenarios that share sufficient similarities that they can usefully be aggregated for the purpose of a specific analysis.

Scenario—A subset of the set of all possible futures of the disposal system that contains futures resulting from a specific combination of FEPs.

Screening Decision—A statement of whether the FEP is included in the quantitative TSPA models or excluded from the TSPA on specific criteria provided by the regulations.

Screening Justification—Applicable to excluded FEPs. A discussion of the technical basis for exclusion.

Seismic Scenario Class—A scenario class consisting of FEPs that represent one or more seismic events, but no igneous or early failure events, and also includes retained nominal features and processes.

TSPA Disposition—Applicable to included FEPs. A summary discussion of the implementation of the FEP in the TSPA.

Unlikely FEP—A FEP that has less than 1 chance in 10 and at least one chance in 10,000 of occurring within 10,000 years of disposal as per 10 CFR 63.342 [DIRS 180319].

Very Unlikely FEP—A FEP that has less than one chance in 10,000 of occurring within 10,000 years of disposal as per 10 CFR 63.102(j) [DIRS 180319].