OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL COVER SHEET

Complete Only Applicable Items

1. QA: QA

2. X Analysis — Check all that apply

Type of Analysis	☐	Engineering
	X	Performance Assessment
	☐	Scientific
Intended Use of Analysis	☐	Input to Calculation
	☐	Input to another Analysis or Model
	☐	Input to Technical Document
	X	Input to other Technical Products

Describe use:
This AMR is intended to summarize the decision, arguments, and disposition of FEPs in the TSPA-SR
It also provides input into the YMP FEP Database

3. ☐ Model — Check all that apply

Type of Model	☐ Conceptual Model	☐ Abstraction Model
	☐ Mathematical Model	☐ System Model
	☐ Process Model	
Intended Use of Model	☐ Input to Calculation	
	☐ Input to another Model or Analysis	
	☐ Input to Technical Document	
	☐ Input to other Technical Products	

Describe use:

4. Title:
Disruptive Events FEPs

5. Document Identifier (including Rev. No. and Change No., if applicable):
ANL-WIS-MD-000005 REV 00

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OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD

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CONTENTS (continued)

TABLES

ACRONYMS AND ABBREVIATIONS

Acronyms

AMR	Analysis/Model Report
AP	Administrative Procedure
CFR	Code of Federal Regulations
CRWMS	Civilian Radioactive Waste Management System
DE	Disruptive Event
DOE	Department of Energy
DRKBA	Discrete Regional Key Block Analysis
EBS	Engineered Barrier System
EPA	Environmental Protection Agency
ESF	Exploratory Studies Facility
FEP	Feature, Event, or Process
FR	Federal Register
IRSR	Issue Resolution Status Report
LADS	License Application Design Selection
M&O	Management and Operating Contractor
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
OCRWM	Office of Civilian Radioactive Waste Management
OECD	Organization for Economic Co-operation and Development
PMR	Process Model Report
PSHA	*Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada*
QAP	Quality Administrative Procedure
QARD	Quality Assurance Requirements and Description
RMEI	Reasonably Maximally Exposed Individual
SZ	Saturated Zone

ACRONYMS AND ABBREVIATIONS (continued)

TBV	To Be Verified
TSPA	Total System Performance Assessment
TSPA-SR	Total System Performance Assessment-Site Recommendation
UDEC	Universal Distinct Element Code
UZ	Unsaturated Zone
YAP	Yucca Mountain Administrative Procedure
YMP	Yucca Mountain Project

Abbreviations

ka	thousand years (before present)
km	kilometer
k.y.	thousand years (duration)
m	meter
Ma	million years (before present)
mm/yr	millimeters per year
MPa	megapascals (a unit of pressure)
M.y.	million years (duration)
Tptpmn	Topopah Spring Tuff, crystal-poor member, middle nonlithophysal
Tptpll	Topopah Spring Tuff, crystal-poor member, lower lithophysal
Tptpln	Topopah Spring Tuff, crystal-poor member, lower non lithophysal
yr	year

1. PURPOSE

Under the provisions of the U.S. Department of Energy's (DOE's) *Revised Interim Guidance Pending Issuance of New U. S. Nuclear Regulatory Commission (NRC) Regulations (Revision 01, July 22, 1999), for Yucca Mountain, Nevada* (Dyer, 1999: and herein referred to as DOE's Interim Guidance), the U.S. Department of Energy (DOE) must provide a reasonable assurance that the performance objectives for the Yucca Mountain Project (YMP) can be achieved for a 10,000-year post-closure period. This assurance must be demonstrated in the form of a performance assessment that (1) identifies the features, events, and processes (FEPs) that might affect the performance of the geologic repository, (2) examines the effects of such FEPs on the performance of the geologic repository, and (3) estimates the expected annual dose to a specified receptor group. The performance assessment must also provide the technical basis for inclusion or exclusion of specific FEPs from the performance assessment.

Although not defined or specified in DOE's Interim Guidance (Dyer 1999), YMP Total System Performance Assessment (TSPA) has chosen to satisfy the above-stated performance assessment requirements by adopting a scenario-development process. This decision was made based on the YMP TSPA adopting a definition of "scenario" as a subset of the set of all possible futures of the disposal system that contains the futures resulting from a specific combination of FEPs. The DOE has chosen to adopt a scenario-development process based on the methodology developed by Cranwell et al. (1990) for the NRC. The first step of the scenario-development process is the identification of FEPs potentially relevant to the performance of the Yucca Mountain repository (see Section 1.2). The second step includes the screening of each FEP, and reaching a Screening Decision of either *Include* in or *Exclude* from (see Section 1.3) further consideration in the TSPA.

The primary purpose of this Analysis/Model Report (AMR) is to identify and document the analysis, Screening Decision, and TSPA Disposition or Screening Argument for the 21 FEPs that have been recognized as Disruptive Events FEPs (described in Section 1.1). The Screening Decisions, and TSPA Disposition and Screening Argument of the subject FEPs will be catalogued separately in a project-specific FEPs database (see Section 1.4). This AMR and the database are being used to document information related to FEPs Screening Decisions, and TSPA Disposition and Screening Argument and to assist reviewers during the licensing-review process. This AMR also provides input to the Disruptive Events (DE) Report.

1.1 SCOPE

This AMR has been prepared to satisfy the FEP screening documentation requirements in the Work Scope/Objectives/Tasks section of the Development Plan entitled *Evaluate/Screen Tectonic FEPs* TDP-WIS-MD-0028 (CRWMS M&O 1999a).

The current FEPs list consists of 1786 entries as described in Section 1.2. The FEPs have been classified as Primary and Secondary FEPs (as described in Section 1.2) and have been assigned to various Process Model Reports (PMRs). The assignments were based on the nature of the FEPs so that the analysis and disposition for each FEP reside with the subject-matter experts in the relevant disciplines. The disposition of FEPs other than Disruptive Events FEPs is documented in AMRs prepared by the responsible PMR groups. Several relevant FEPs do not fit neatly into the existing PMR structure. An example is criticality, and it is treated in FEP assignments as if it were a separate item. Some FEPs were best assigned to the TSPA itself (i.e., system-level FEPs), rather than to its component models.

In the original FEPs assignment, 26 FEPs were originally designated as Disruptive Events FEPs. Five of the FEPs were subsequently reassigned to the System-Level FEPs report. This AMR addresses the 21 Primary FEPs that have been identified as Disruptive Events FEPs and assigned to the Disruptive Events FEP report (this document). The 21 Primary Disruptive Events FEPs addressed in this AMR are identified in Table 1.

These FEPs represent natural-systems processes that have the potential to produce disruptive events (defined as "an *Include* FEP that has a probability of occurrence during the period of performance less than 1.0, but greater that the probability criterion of $10^{-4}/10^{4}$year"). The FEPs are related to geologic processes such as structural deformation, seismicity, and igneous activity. Of the 21 Primary Disruptive Events FEPs, 16 are addressed explicitly and fully in this AMR. The remaining 5 Primary Disruptive Events FEPs are addressed in this document with only short summaries and with references to the related AMRs that provide the explicit and full discussion of the FEP. This approach was taken because these 5 FEPs have significant overlap to the related subject areas and are better discussed in the context of the referenced AMR.

Table 1. Primary Disruptive Events FEPs

YMP FEP Database Number	FEP Name
1.2.01.01.00	Tectonic activity—large scale
1.2.02.01.00	Fractures
1.2.02.02.00	Faulting
1.2.02.03.00	Fault movement shears waste container
1.2.03.01.00	Seismic activity
1.2.03.02.00	Seismic vibration causes container failure
1.2.03.03.00	Seismicity associated with igneous activity
1.2.04.01.00	Igneous activity
1.2.04.02.00*	Igneous activity causes changes to rock properties
1.2.04.03.00	Igneous intrusion into repository
1.2.04.04.00	Magma interacts with waste
1.2.04.05.00	Magmatic transport of waste
1.2.04.06.00	Basaltic cinder cone erupts through the repository
1.2.04.07.00	Ashfall
1.2.10.01.00*	Hydrologic response to seismic activity
1.2.10.02.00	Hydrologic response to igneous activity
2.1.07.01.00	Rockfall (large block)
2.1.07.02.00	Mechanical degradation or collapse of drift
2.2.06.01.00*	Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock
2.2.06.02.00*	Changes in stress (due to thermal seismic, or tectonic effects) produce change in permeability of faults

Table 1. Primary Disruptive Events FEPs (continued)

YMP FEP Database Number	FEP Name
2.2.06.03.00*	Changes in stress (due to seismic or tectonic effects) alter perched water zones

Notes:
* FEP may also be addressed in related FEPs reports as noted in the *YMP FEP Database* 1999b

1.2 FEPS IDENTIFICATION AND ANALYSIS

For the YMP TSPA, a scenario is being defined as a subset of the set of all possible futures of the disposal system that contains the futures resulting from a specific combination of FEPs. The first step of the scenario-development process is the identification of FEPs potentially relevant to the performance of the Yucca Mountain repository. The most current list of FEPs is contained in the *YMP FEP Database* (CRWMS M&O 1999b).

The development of a comprehensive list of FEPs relevant to the YMP is an ongoing process based on site-specific information, guidance documents, and proposed regulations. The *YMP FEP Database* (CRWMS M&O 1999b) contains 1786 entries, derived from the following sources:

- General FEPs from other international radioactive waste disposal programs
- YMP-specific FEPs identified in YMP literature
- YMP-specific FEPs identified in technical workshops

The YMP FEPs list was initially populated with FEPs compiled by radioactive waste programs in the U.S. and other nations. The Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD) maintains an electronic FEP database that currently contains 1261 FEPs from seven programs, representing the most complete attempt internationally at compiling a comprehensive list of FEPs potentially relevant to radioactive waste disposal (SAM 1997). The NEA FEP database currently exists in draft form only, but the publications of the seven disposal programs that contributed FEPs to the compilation contain descriptions of the FEPs. These programs are the Atomic Energy of Canada, Ltd. (AECL; Goodwin et al. 1994); a “Scenario Working Group” of the NEA (NEA 1992); a joint effort by the Swedish Nuclear Power Inspectorate (SKI) and Swedish Nuclear Fuel Management Company (SKB) (Andersson 1989); a study of deep geologic disposal by SKI (Chapman et al. 1995); an assessment done by Her Majesty’s Inspectorate of Pollution (HMIP) for the intermediate and low-level site proposed in the United Kingdom by U.K. Nirex, Ltd. (Miller and Chapman 1993); an analysis by the National Cooperative for the Disposal of Radioactive Waste (NAGRA) of Switzerland for the proposed Kristallin-1 project (NAGRA 1994); and the U.S. DOE Waste Isolation Pilot Plant (WIPP) program (DOE, 1996).

The 1261 FEPs identified by these programs have been organized by the NEA FEP database working group into a hierarchical structure that is defined by 150 layers, categories, and headings. The *YMP FEP Database* uses the same structure (see Section 1.4). Each of the layers, categories, and headings is an individual entry in the *YMP FEP Database*, as are the 1261 FEPs, which are organized under them. Therefore, the *YMP FEP Database* contains a total of 1411 entries that were adopted from the NEA database.

The YMP FEP list was supplemented with YMP-specific FEPs identified in past YMP work during site characterization and preliminary performance assessments (Barr 1999). Because Yucca Mountain is an unsaturated, fractured-tuff site, many of these FEPs represent events and processes not otherwise included in the international compilation. The supplemental entries resulted from a search of YMP literature in 1998 and identified 293 additional FEP entries. Relevant FEPs from the 1704 entries identified from the NEA database and YMP literature were then taken to a series of technical workshops convened between December 1998 and April 1999. At these workshops, the relevant FEPs were reviewed and discussed by subject matter experts within the project. As a result of these discussions, workshop participants proposed 82 additional YMP-specific FEPs. Many of these additional FEPs were developed informally during roundtable discussions at the workshops and have no formal documentation other than workshop notes, but are included in the FEPs list.

In summary, the *YMP FEP Database* (CRWMS M&O 1999b) contains 1786 entries, comprised of 151 layers, categories, and headings (which define the hierarchical structure of the database as described in Section 1.4) and 1635 specific feature, event, and/or process entries.

Under the definition adopted for the Yucca Mountain TSPA, a scenario is defined as a subset of the set of all possible futures of the disposal system that contain the futures resulting from a specific combination of FEPs. There is no uniquely correct level of detail at which to define scenarios or FEPs. Coarsely defined FEPs result in fewer, broad scenarios, whereas narrowly defined FEPs result in many narrow scenarios. If the FEPs are too narrowly defined, the narrow definition may result in and otherwise relevant FEP being excluded because of low probability or low consequence caused by the narrow definition. Coarsely defined FEPs are preferable because probability arguments and consequence arguments developed at the coarser scale tend to conservatively bias the TSPA toward including the FEPs. For efficiency, both FEPs and scenarios should be aggregated at the coarsest level at which a technically sound argument can be made that is adequate for the purposes of the analysis.

For YMP FEP screening purposes, each FEP has been identified as either a Primary or Secondary FEP. Primary FEPs are the coarsest aggregation of FEPs suitable for screening for the YMP project and for which the project proposes to develop detailed screening arguments. The classification and description of Primary FEPs strive to capture the essence of all the secondary FEPs that are aggregated into the Primary FEP. Secondary FEPs are FEPs that are either completely redundant or that can be reasonably aggregated into a single Primary FEP. By working to the Primary FEP description, the subject-matter experts assigned to the Primary FEP also address all relevant secondary FEPs, and arguments for secondary FEPs can be included in the Primary FEP analysis and disposition. For example, the coarse Primary FEP "Faulting" can be used appropriately to resolve multiple and redundant secondary FEPs that address various types and occurrences of faults in the Yucca Mountain area. It can also be used to provide analysis of narrowly-defined Secondary FEPs that stem from related geologic processes, such as creation of new faults and reactivation of existing faults.

To perform the screening and analysis, the FEPs have been assigned based on the PMR structure so that the analysis, Screening Decision, and TSPA Disposition reside with the subject-matter experts in the relevant disciplines. The TSPA recognizes that FEPs have the potential to affect multiple facets of the project, may be relevant to more than one PMR, or may not fit neatly within the PMR structure. For example, many FEPs affect waste form, waste package, and the Engineered Barrier System (EBS). Rather than create multiple separate FEPs, the FEPs have been assigned, as applicable, to one or more process-model groups, which are responsible for the PMRs.

At least two approaches may be used to resolve overlap and interface problems of multiply-assigned FEPs. FEP owners from different process-model groups may decide that only one process-model group will address all aspects of the FEP, including those relevant to other PMRs. Alternatively, FEP owners may each address only those aspects of the FEP relevant to their area. In either case, the FEP AMR produced by each process-model group lists the FEP and summarizes the screening result, citing the appropriate work in related AMRs as needed.

In the original FEPs assignment, 26 FEPs were original designated as Disruptive Events FEPs. Five of the FEPs were subsequently reassigned to the System-Level FEPs report. This AMR addresses the 21 Primary FEPs that have been identified as Disruptive Events FEPs and assigned to the Disruptive Events FEP report (this document). Of the 21 Primary Disruptive Events FEPs, 16 are addressed explicitly and fully in this AMR. As previously stated, five of the Primary Disruptive Events FEPs are addressed explicitly and fully by other AMRs. The five FEPs in question concern changes in rock properties due to seismic or igneous activity, or changes in hydrologic parameters due to changes in the stress field.

1.3 FEPS SCREENING PROCESS

As described in Section 1.2, the first step in the scenario-development process was the identification and analysis of FEPs. The second step in the scenario-development process includes the screening of each FEP against project criteria. Each FEP is screened against criteria that are stated in DOEs Interim Guidance (Dyer, 1999) and in the U.S. Environmental Protection Agency's (EPA) proposed rule 40 CFR Part 197 (64 FR 46975 - 47016). The screening criteria are discussed in more detail in Section 4.2 and are summarized here.

- Is the FEP specifically ruled out by the guidance or proposed regulations, or contrary to the stated guidance or regulatory assumptions?

- Does the FEP have a probability of occurrence less than 10^{-4} in 10^{4} years?

- Will there be a negligible change to the resulting expected annual dose if the FEP is omitted? (Note: See Section 4.2.2 for additional explanation. The terms“significantly changed” and “changed significantly” are undefined terms in the DOE's Interim Guidance and in the EPA’s proposed regulations. These terms are inferred to be equivalent to having no or negligible effect.)

The screening criteria contained in DOE's Interim Guidance (Dyer 1999) and in the proposed 40 CFR Part 197 (64 FR 46976) are relevant to many of the FEPs. FEPs that are contrary to DOE’s

Interim Guidance, or specific proposed regulations, regulatory assumptions, or regulatory intent are excluded from further consideration. Examples include: the explicit exclusion of consideration of all but a stylized scenario to address treatment of human intrusion (Dyer 1999, Section 113(d)), assumptions about the critical group to be considered in the dose assessment (Dyer 1999, Section 115), and the intent that the consideration of "the human intruders" be excluded from the human-intrusion assessment (64 FR 8640, Section XI. Human Intrusion).

Probability estimates used in the FEPs screening process are based on a technical analysis (either by consideration of bounding conditions or a quantitative analysis), and, in some cases, involve a formalized expert elicitation (such as seismic- and volcanic-hazard probabilities). Probability arguments, in general, require including quantitative information about the spatial and temporal scale of the event or process, the magnitude of the event or process, and the response of the repository features to such events and processes. For the TSPA, the probability of an event is in essence the product of the hazard level (e.g., for a seismic event this would be the magnitude of ground motion or velocity expressed as an annual exceedance probability) and the resulting impact (e.g., unacceptable damage to the drip shield expressed as a fragility probability).

If a FEP can be shown to have negligible impact on UZ or SZ flow and transport, waste-package integrity, or other components of the engineered barrier system (EBS) or natural barrier system, then there is no mechanism for the FEP to increase the calculated dose in the TSPA. Consequently, the FEP has a negligible impact on the performance assessment, and the FEP can be excluded based on low consequence. Various methods to demonstrate negligible impact include TSPA sensitivity analyses, modeling studies outside of the TSPA, reasoned arguments based on literature research, and on expertise of the subject matter experts (including, in some cases, the expert elicitation process). For example, erosion is known to occur, but is it of any consequence to the repository? The question could be evaluated in several ways, the simplest perhaps by considering bounding rates of erosion reported in various geologic or soil-science literature, but on a case-by-case basis. More complicated processes, such as igneous activity, may require detailed analyses conducted specifically for the YMP.

Low-consequence arguments are often made by demonstrating that a particular FEP has no effect on the distribution of an intermediate performance measure in the TSPA. For example, by demonstrating that including a particular waste form has no effect on the concentrations of radionuclides transported from the repository in the aqueous phase, it is also demonstrated that including this waste form in the inventory would not affect other performance measures such as doses, that are dependent on concentration. Explicit modeling of the characteristics of this waste form could therefore be excluded from further consideration in the TSPA, where concentration of radionuclides has a primary impact on dose. The last of the three criteria stated above allow FEPs to be excluded from further consideration, if the expected annual dose would not be “significantly changed” by their omission. The terms “significantly changed” and “changed significantly” are undefined terms in the DOE's Interim Guidance and in the EPA’s proposed regulations. These terms are inferred for FEPs screening purposes to be equivalent to having no or negligible effect. Because the relevant performance measures differ for different FEPs (e.g., effects on performance can be measured in terms of changes in concentrations, flow rates, travel times, or other measures as well as overall expected annual dose), there is no single quantitative test of “significance.”

Based on the three criteria stated above, the screening decision for the FEP is then determined as either *Include* or *Exclude*. If the response to each of these criteria is "no" then the screening decision of the FEP is *Include*. Inclusion of a FEP in the TSPA signifies that the potential effects of FEP on repository performance are specifically included in performance-related and dose-related calculations. If the screening decision is *Include*, the FEP must be considered either in the nominal scenario (i.e., the scenario that contains all expected FEPs and no disruptive FEPs), in the disruptive scenario (i.e., any scenario that contains all expected FEPs and one or more disruptive FEPs), or as appropriate, in the human intrusion scenario. Expected FEPs are those *Include* FEPs that, for the purposes of the TSPA, are assumed to occur with a probability equal to 1.0 during the period of performance. A disruptive FEP is an *Include* FEP that has a probability of occurrence during the period of performance of less than 1.0, but greater that the criteria cutoff of $10^{-4}/10^{4}$year. Exclusion of a FEP signifies that the FEP has been demonstrated to satisfy one or more of the screening criteria listed above. In that case, the FEP is therefore no longer considered in the TSPA evaluation.

Because the Primary FEPs are the coarsest aggregate suitable for analysis, situations may result in which a given Primary FEP contains some Secondary FEPs that are *Include* and some that are *Exclude.* Or in some situations, existing FEPs (such as existing fractures) are *Include* in the TSPA, but changes to the existing FEP (such as changes in fracture aperture) have been demonstrated to be of no significance and are considered as *Exclude.* In these situations, the screening decision will specify which elements are *Include* and which are *Exclude.* In some instances, a screening decision may be based on preliminary calculations or very strong and reasoned arguments that remain to be verified. In these instances, the *Exclude* screening decision will also specify the disposition as "TBV."

1.4 ORGANIZATION OF FEP DATABASE

Under a separate task, the TSPA team is constructing an electronic database to contain information related to FEP Screening Decisions, and TSPA Dispositions and Screening Arguments, and to assist project reviewers during the license-review process (i.e., the *YMP FEP Database* (CRWMS M&O 1999b))

The structure of the *YMP FEP Database* follows the NEA classification scheme, which uses a hierarchical structure of layers, categories, and headings. Alphanumeric identifiers (called the "NEA category") previously used have been retained in the database for traceability purposes. The *YMP FEP Database* (CRWMS M&O 1999b) has 4 layers, 12 categories, and 135 headings. The relationships between these layers, categories, and selected headings are shown below in Table 2

Table 2. YMP Database Structure

Layers	Categories	Total Number of Headings (and general heading descriptions*)
0. Assessment Basis		10 (timescales, spatial domain, regulatory requirements, model and data issues)
1. External Factors	1.1 Repository Issues	13 (design, excavation/construction, closure/sealing, monitoring, quality control)
	1.2 Geologic Processes and Effects	10 (tectonics, seismicity, volcanism, hydrologic response to geologic processes)
	1.3 Climatic Processes and Effects	9 (climate change)
	1.4 Future Human Actions (Active)	11 (human intrusion, water management, social and technological development)
	1.5 Other	3 (meteorite impact, earth tides)
2. Disposal System Domain: Environmental Factors	2.1 Wastes and Engineered Features	14 (inventory, waste form, waste package, backfill, drip shield, in-drift processes such as mechanical, hydrological, chemical, biological, thermal, gas, criticality)
	2.2 Geologic Environment	14 (excavation-disturbed zone, rock properties, geosphere processes such as mechanical, hydrological, chemical, biological, thermal, gas, criticality)
	2.3 Surface Environment	13 (topography, soil, surface water, biosphere)
	2.4 Human Behavior	11 (human characteristics, diet, habits, land and water use)
3. Disposal System Domain: Radionuclide / Contaminant Factors	3.1 Contaminant Characteristics	6 (radioactive decay and ingrowth)
	3.2 Contaminant Release/Migration Factors	13 (atmospheric transport)
	3.3 Exposure Factors	8 (drinking water, food, exposure modes, dosimetry, toxicity, radon exposure)

* parenthetical notes are general descriptions of selected headings

Each FEP has been entered as a separate record in the database. Fields within each record provide a unique identification number, a description of the FEP, the origin of the FEP, identification as a Primary or Secondary FEP for the purposes of the TSPA, and references to related FEPs and to the assigned PMRs. Fields also provide summaries of the Screening Arguments with references to supporting documentation and AMRs, and for all retained FEPs, statements of the TSPA Disposition indicating the nature of the treatment of the FEP in the TSPA. The AMRs, however, contain the detailed arguments and descriptions of the TSPA Disposition of the subject FEPs.

Each FEP has also been assigned a unique YMP FEP database number, based on the NEA categories. The database number is the primary method for identifying FEPs, and consists of an eight-digit number. This number has the form x.x.xx.xx.xx and defines layer, category, heading, primary, and secondary entries as follows:

x.0.00.00.00 Layer
x.x.00.00.00 Category
x.x.xx.00.00 Heading (some of these are also Primary FEPs)
x.x.xx.xx.00 Primary FEP (where the first x.x.xx is the overlying Heading)
x.x.xx.xx.xx Secondary FEP (where the first x.x.xx.xx is the overlying primary FEP)

With this numbering scheme, the YMP FEP Database Number always identifies the heading to which a Primary FEP is assigned and the Primary FEP to which a Secondary FEP is aggregated. For example, the Primary FEP entitled "Tectonic Activity-Large Scale" is assigned the unique database number of 1.2.01.01.00. This signifies that it is an external factor (1.x.xx.xx.xx), under the category of geologic processes (1.2.xx.xx.xx), is listed under the heading for Tectonics (1.2.01.xx.xx), and is the first Primary FEP under the heading (1.2.01.01.00). The unique database numbers for the 21 Primary Disruptive Events FEPs are shown in Table 1 (Section 1.1) and are included in the report section headings under Section 6.2.

2. QUALITY ASSURANCE

The activities documented in this AMR were evaluated in accordance with QAP-2-0, *Conduct of Activities* and were determined to be quality affecting and subject to the requirements of the U.S. DOE Office of Civilian Radioactive Waste Management (OCRWM*) Quality Assurance Requirements and Description* (QARD) (DOE 2000). This evaluation is documented in an Activity Evaluation of M&O Site Investigations - (L) (*Conduct of Performance Assessment,* WBS#13012130M2, CRWMS M&O 1999c). Accordingly, the analysis activities documented in this AMR have been conducted in accordance with the Civilian Radioactive Waste Management System Maintenance and Operations (CRWMS M&O) quality-assurance program, using approved procedures identified in the Development Plan entitled *Evaluate/Screen Tectonics FEPs* (CRWMS M&O 1999a)

More specifically, this AMR has been developed in accordance with procedure AP-3.10Q, *Analyses and Models*. All associated records (e.g., data, software, planning) have been submitted per the appropriate procedure cited in AP-3.10Q. Requirements of other procedures included by reference in AP-3.10Q have also been addressed as appropriate. The results of this AMR do not affect the design or performance of any permanent items.

The list of the 21 Primary Disruptive Events FEPs addressed in this AMR was derived from the *YMP FEP Database* REV. 00A, which was an uncontrolled version. The current and controlled version of the *YMP FEP Database* is REV. 00C (CRWMS M&O 1999b). REV. 00C derives from REV 00A and there are no differences that affect any of the FEP Descriptions presented in this AMR. REV. 00 of the FEPs database is currently scheduled as a Level 3 Milestone, deliverable to DOE as part of the Total System Performance Assessment-Site Recommendation (TSPA-SR) deliverables and will be maintained in accordance with YAP-SV.1Q, *Control of the Electronic Management of Data*.

3. COMPUTER SOFTWARE AND MODEL USAGE

This AMR uses no computational software; therefore, this analysis is not subject to software controls. The analyses and arguments presented herein are based on guidance and proposed regulatory requirements, results of analyses presented and documented in other AMRs, or technical literature.

This AMR was developed using only commercially approved software (Microsoft® *Word 97*) for word processing, which is exempt from qualification requirements in accordance with AP-SI.1Q, *Software Management*. There were no additional applications (Routines or Macros) developed using this commercial software.

4. INPUTS

4.1 DATA AND PARAMETERS

The nature of the FEPs Screening Arguments and TSPA Dispositions is such that cited data and values are often used to support reasoned FEP Screening Arguments or TSPA Dispositions, rather than being used as direct inputs to computational analysis or models. Consequently, the data cited in the FEPs Screening Arguments and TSPA Dispositions are largely corroborative in nature, and the FEP Screening Decisions will not be affected by any anticipated uncertainties in the cited data. Consequently, the data are not listed as inputs in this section, but are cited in the individual FEPs screening arguments and dispositions.

Two TBV items are associated with the analysis cited in the screening for the FEPs for Rockfall (2.1.07.01.00) and Mechanical Degradation or Collapse of Drift (2.1.07.02.00). TBV-3472, which is the result of using unqualified fracture inputs in the Discrete Region Key Block Analysis (DRKBA) program, is not expected to impact the results from the FEPs screening analysis. Although the fracture inputs have not been qualified, the inputs are based on final, qualified fracture data. The development of the fracture inputs is in the process of being documented according to a qualified procedure, and no significant changes to the inputs are expected. TBV-1290, which is the result of using the unqualified code, DRKBA Version 3.3, is the primary TBV item impacting the conclusions of the *Drift Degradation Analysis*, ANL-EBS-MD-000027 (CRWMS M&O 2000a). Substantial modifications to the code as a result of the qualification process are not anticipated; therefore, the resolution of TBV-1290 is not expected to significantly impact the results presented in this FEPs screening argument. Based on a review of the TBV requirements as presented in AP-3.15Q, these items are not required to be carried forward as TBV in this document.

The results of the analysis presented in *Fault Displacement Effects on Transport in the Unsaturated Zone*, ANL-NBS-HS-000020 (CRWMS M&O 2000b Section 7) have also been designated TBV because the analysis was performed using the 3-D UZ flow-and-transport model previously utilized in the TSPA-VA (CRWMS M&O 1998c), which is considered as a non-Q work product. The UZ flow-and-transport model to be used in the TSPA-SR is being modified and, if used for the fault-displacement-effects analysis, could yield different results. However, for FEPs screening purposes, the use of the TSPA-VA model was expedient and appropriate for evaluating the significance of fault-displacement effects. Based on a review of the TBV requirements as presented in AP-3.15Q, these items are not required to be carried forward as a TBV in this document.

4.2 CRITERIA

This AMR complies with the DOE's Interim Guidance (Dyer 1999). The Subparts of the Interim Guidance that apply to this analysis are those pertaining to the characterization of the Yucca Mountain site (Dyer 1999, Subpart B, Section 15). In particular, relevant parts of the guidance include the compilation of information regarding geology, hydrology, and geochemistry of the site (Dyer 1999, Subpart B, Section 21(c)(1)(ii)), and the definition of geologic, hydrologic, and geochemical parameters and conceptual models used in performance assessment (Dyer 1999, Subpart E, Section 114(a)).

Technical screening criteria are provided in DOE's Interim Guidance (Dyer 1999) and have also been identified by the NRC in proposed 10 CFR Part 63 (64 FR 8640) and by the EPA in 40 CFR Part 197 (64 FR 46976). Both proposed regulations specifically allow the exclusion of FEPs from the TSPA if they are of low probability (less than one chance in 10,000 of occurring in 10,000 years ($10^{-4}/10^{4}$ years)) or if occurrence of the FEP can be shown to have no significant effect on expected annual dose. There is no quantified definition of "significant effect" in the guidance or proposed regulations.

4.2.1 Low Probability

The probability criterion is explicitly stated in the DOE's Interim Guidance (Dyer 1999, Section 114(d)):

> Consider only events that have at least one chance in 10,000 of occurring over 10,000 years.

The EPA provides essentially the same criterion in proposed 40 CFR §197.40 (64 FR 47016): :

> The DOE’s performance assessments should not include consideration of processes or events that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal.

4.2.2 Low Consequence

Criteria for low consequence screening arguments are provided in DOE's Interim Guidance (Dyer 1999, Section 114(e) and (f)), which indicates that performance assessments shall:

> (e) Provide the technical basis for either inclusion or exclusion of specific features, events, and processes of the geologic setting in the performance assessment. Specific features, events, and processes of the geologic setting must be evaluated in detail if the magnitude and time of the resulting expected annual dose would be significantly changed by their omission.

(f) 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 expected annual dose would be significantly changed by their omission.

The EPA provides essentially the same criteria in proposed 40 CFR §197.40 (64 FR 47016):

> . . . with the NRC's approval, the DOE's performance assessment need not evaluate, in detail, the impacts resulting from any processes and events or sequences of processes and events with a higher chance of occurrence if the results of the performance assessment would not be changed significantly.

The terms "significantly changed" and "changed significantly" are undefined terms in the DOE's Interim Guidance and in the EPA's proposed regulations. These terms are inferred for FEPs screening purposes to be equivalent to having no or negligible effect. Because the relevant performance measures differ for different FEPs (e.g., effects on performance can be measured in terms of changes in concentrations, flow rates, travel times, or other measures as well as overall expected annual dose), there is no single quantitative test of "significance."

4.2.3 Reference Biosphere

Both DOE's Interim Guidance (Dyer 1999) and EPA's proposed regulations specify assumptions (which in effect serve as criteria) pertinent to screening many of the Disruptive Events FEPs. Particularly germane are explicit assumptions regarding the reference biosphere. An assumption pertaining to the characteristics of the reference biosphere is presented in DOE's Interim Guidance in Section 115 (a)(1) (Dyer 1999):

> Features, events, and processes that described the reference biosphere shall be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site.

The EPA has specified a similar assumption in proposed 40 CFR §197.15 (64 FR 47014). . This assumption can be summarized as follows:

> . . . DOE must vary factors related to the geology, hydrology, and climate based on environmentally protective but reasonable scientific predictions of the changes that could affect the Yucca Mountain disposal system over the next 10,000 years.

These criteria are of particular interest because they impose a constraint on the use of probabilistic assessments to the TSPA. For instance, in the *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion* (PSHA) (CRWMS M&O 1998b, Figure 8-3), the integrated summary hazard curve for fault displacement based on the Solitario Canyon fault suggests that the fault displacement for the 10^{-8} annual exceedance probability could potentially be 5 m. However, physical observations of displacements from trench displacements and studies in the Exploratory Studies Facility (ESF), indicate that the maximum per-event displacement over the last 250,000 ky is no larger than 1.3 m (Ramelli et al. 1996, p. Table 4.7.3).

4.2.4 Critical Group

The characteristics of the critical group to be used in exposure calculations are given in DOE's Interim Guidance (Dyer 1999, Section 115(b)). Pertinent to the Disruptive Events FEPs are the guidance that:

> The critical group shall reside within a farming community located approximately 20 km south from the underground facility (in the general location of U.S. route 95 and Nevada Route 373, near Lathrop Wells, Nevada) (Dyer 1999, Section 115(b)(1))

The EPA-specified assumptions regarding biosphere characteristics are provided in proposed 40 CFR §197.21(a-c) (64 FR 47015) and describe the "reasonably maximally exposed individual" (RMEI). The characteristics of the RMEI are similar to those described for the critical group, but there is a significant difference in the approach of using a "critical group" versus the RMEI concept. The difference lies in the conceptual approach to calculating dose, the explanation of which is beyond the scope of this AMR.

For the Disruptive Events FEPs, the distance to the critical group (specified as 20 km) is the primary criterion of interest, and it is not significantly different from the locations of the RMEI proposed by EPA in proposed 40 CFR §197.37, Alternative 2 (64 FR 46796), which states that the RMEI " . . . lives within one-half kilometer of the junction of U.S. Route 95 and Nevada State Route 373." This location is approximately 20 km from the proposed repository. Consequently, resolution of the differences in approach (i.e., critical group versus RMEI) is unlikely to affect any screening decisions provided for the Disruptive Events FEPs.

4.3 CODES AND STANDARDS

There are no Codes or Standards directly applicable to this analysis.

5. ASSUMPTIONS

There are four general assumptions used in screening of the Disruptive Events FEPs.

Assumption 5.1: As directed by DOE's Interim Guidance (Dyer 1999, Section 114(l)), the TSPA assumes that the evolution of the geologic setting consistent with present knowledge of natural processes. For the Disruptive Events FEPs, there is an assumption that the tectonic strain rates at Yucca Mountain will remain unchanged through the repository performance period.

This assumption is particularly germane to Disruptive Events FEPs because the FEPs are concerned with geologic processes (e.g., tectonic, seismic, and igneous processes). Additionally the TSPA inherently assumes that existing knowledge of natural process is sufficient to adequately quantify future states of the system.

This assumption is justified because it is consistent with the existing guidance and screening criteria. As discussed in the context of specific FEPs in Section 6, available information indicates that strain rates are likely to decrease throughout the performance period. The assumption that strain rates will remain unchanged is therefore conservative.

Assumption 5.2: Design parameters can be used to justify an *Exclude* FEP screening decision, if the design parameter eliminates or alleviates the FEP (i.e., in some cases the screening decision is design dependent).

For the TSPA, the YMP defines an event as "a natural or anthropogenic 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." Inherent in this definition is an interaction between the phenomenon (or FEP) and some component of the repository system which leads to decreased performance. The design parameters determine, to some extent, the degree of interaction of the geologic process with the waste packages. If a design parameter (such as set-backs from faults) is instituted which eliminates or alleviates the interaction, then the FEP Screening Decision can be determined on that basis.

This assumption is particularly germane to FEPs involving potential failure of containers due to some triggering tectonic event, such as FEP 1.2.02.03.00, "Fault movement shears waste container" and 1.2.03.02.00, "Seismic vibration causes container failure." The FEP "Fault movement shears waste containers" is excluded based on the assumption that fault set-backs as specified in *Subsurface Facility System Description Document* BCA000000-01717-1705-00014 (CRWMS M&O 1998a, Sections 1.2.1.7 and Section 1.2.1.8) will be implemented. It is relevant to FEP 1.2.03.02.00, because the design requirements for waste packages are to consider post-closure performance requirements.

This assumption is justified because (1) FEPs can be defined temporally, spatially, and in magnitude; (2) the phenomena and effect of the interaction can be quantified (or at least bounded) and, therefore, incorporated into the design; (3) the implementation of the design and changes to the design are subject to a performance-confirmation process; and (4) the "as-built" design can be verified (see Assumption 5.3).

This assumption is also justified based on the conditions specified in DOE's Interim Guidance (Dyer 1999, Section 21 (b)(6)), which includes a requirement for a description of the quality assurance program to be applied to structures, systems, and components. Regardless of the quality-assurance-program requirement, the TSPA includes the possibility that engineered systems may not perform entirely as designed for the full 10,000 years. For example, the premature failure of some waste-packages is included in the TSPA through the probabilistic treatment of waste-package degradation.

Assumption 5.3: The TSPA is based on an assumption that the repository will be constructed, operated, and closed according to the design used as the basis for the FEP screening.

Unless a FEP can be excluded because of a low probability of the phenomenon ever occurring, the FEP screening decision is based, at least in part, on the design used for the comparison. For example, the *License Application Design Selection (LADS) Report*, B00000000-01717-4600-00123 REV00 (CRWMS M&O 1999d, p. 0-21 to 0-26 and Section 7) indicates that the repository design includes backfill of the drift and installation of drip shields. These design features minimize the potential for rockfall or drift degradation (FEPs 2.1.07.01.00 and 2.1.07.02.00) to damage the containers. The presence of these components strengthens the *Exclude* screening decision.

This assumption is justified because a change in the design may require a reevaluation of the screening decision for FEPs that are dependent on design requirements.

Assumption 5.4: For seismic-related FEPs, it is assumed that the probability criterion of $10^{-4}/10^{4}$ yr refers to the probability of unacceptable performance, which for a seismic event, is the product of the hazard level (e.g., ground motion) and the consequences (e.g., unacceptable damage to drip shield). It is also assumed that $10^{-4}/10^{4}$ yr is equivalent to a 10^{-8} annual exceedance probability.

In essence, this assumption advocates the convolution of the hazard probabilities provided by the PSHA (CRWMS M&O 1998b, Section 7) with the system fragilities (fragility curves), or a similar type of performance measure. If it can be shown that the probability of unacceptable performance is below the threshold, then the FEP can be excluded. The assumption of equivalence of $10^{-4}/10^{4}$ yr to the 10^{-8} annual exceedance probability is appropriate if the possibility of events is equal for any given year.

This assumption is used for the seismic-related FEP 1.2.03.02.00, "Seismic vibration causes container failure."

6. ANALYSES

The method used for this analysis is a combination of qualitative and quantitative screening of FEPs. The analyses are based on the criteria provided in the DOE's Interim Guidance, criteria proposed by the NRC in 10 CFR Part 63 (64 FR 8640) and by the EPA in 40 CFR Part 197 (64 FR 46976). The criteria are used to determine whether or not each FEP should be included in the TSPA.

For FEPs that are *Exclude* based on proposed regulatory requirements (e.g., requirements regarding the location and composition of the critical group as described in Section 4.2.4), the screening argument includes the regulatory reference and a short discussion of the applicability of the standard. No Primary Disruptive Events FEPs have an *Exclude* Screening Decision based solely on proposed regulatory requirements or regulatory-specified assumptions.

For FEPs that are *Exclude* based on DOE's Interim Guidance (Dyer, 1999) or criteria from EPA’s proposed regulations, the Screening Argument includes the basis of the exclusion (low probability (Section 4.2.1), or low consequence (Section 4.2.2)) and provides a short summary.

As appropriate, Screening Arguments cite work done outside this activity, such as in other AMRs. A more detailed discussion is typically provided in the Analysis/Discussion section.

For FEPs that are *Include*, the TSPA Disposition discussion for each FEP in Section 6.2 describes how the FEP has been incorporated in the process models or the TSPA abstraction.

6.1 ALTERNATIVE APPROACHES

To ensure clear documentation of the treatment of potentially relevant future states of the system, the DOE has chosen to adopt a scenario-development process based on the methodology developed by Cranwell et al. (1990) for the NRC. The approach is fundamentally the same as that used in many performance assessments. The approach has also been used by the DOE for the Waste Isolation Pilot Plant (DOE 1996), by the NEA, and by other radioactive waste programs internationally (e.g., Skagius and Wingefors 1992). Regardless of the "scenario" method chosen for the performance assessment, the initial steps in the process involve development of a FEPs list, and screening of the FEPs list for inclusion or exclusion (see Section 1.2).

The approach used to identify, analyze, and screen the FEPs (as described in Section 1.2 and 1.3) was also considered. Alternative classification of FEPs as Primary or Secondary FEPs is possible in an almost infinite range of combinations. Classification into Primary and Secondary FEPs is based primarily on redundancy and on subject matter. Subsequent assignment and analysis by knowledgeable subject-matter experts for evaluation appeared to be the most efficient methodology for ensuring a comprehensive assessment of FEPs as they relate to the TSPA. Alternative classification and assignments of the FEPs are entirely possible, but would still be based on subjective judgement. Alternative approaches for determining probabilities and consequences used as a basis for screening are discussed in Section 6.2 under the individual FEP analysis.

In practice, regulatory-type criteria were examined first, and then either probabilities or consequences were examined. FEPs that are retained on one criterion were also considered against the others. Consequently, the application of the analyst's judgment regarding the order in which to apply the criteria does not affect the final decision. Allowing the analyst to choose the most appropriate order to apply the criteria prevents needless work, such as developing quantitative probability arguments for low-consequence events or complex, consequence models for low-probability events. For example, there is no need to develop detailed models of the response of waste packages to fault shearing, if it can be shown that fault-shearing events have a probability below the criteria threshold.

Regardless of the specific approach chosen to perform the screening, the screening process is in essence a comparison of the FEP against the criteria specified in Section 4.2. Consequently, the outcome of the screening is independent of the particular methodology or assignments selected to perform the screening.

Alternative interpretations of data as they pertain directly to the FEPs screening are provided in the Analysis and Discussion section for each FEP, as discussed below. The FEPs screening decisions may also rely on the results of analyses performed and documented as separate activities. Alternate approaches related to separate activities and analyses are addressed in the specific AMRs for those analyses and are not discussed in this AMR.

6.2 DISRUPTIVE EVENTS FEPS EVALUATION AND ANALYSIS

This AMR addresses the 21 Primary FEPs that have been identified as Disruptive Events FEPs. Primarily, these FEPs represent areas of natural-systems processes that have the potential to produce disruptive events that could impact repository performance. The FEPs are related to geologic processes such as structural deformation, seismicity, and igneous activity. Of these 21 Primary FEPs, 16 are addressed explicitly and fully in this document.

The remaining 5 Primary FEPs are being addressed in other AMRs due to overlap in related subject areas: These 5 FEPs concern geologic processes that can affect rock characteristics. Short summaries for these 5 FEPs are, however, included in this document.

Arguments for Secondary FEPs screening decisions are embedded in the discussion of the Primary FEPs as described in Section 1.3. Secondary FEP descriptions can be obtained from the YMP FEP Database (CRWMS M&O 1999b). All secondary FEPs have been examined and are incorporated into the Primary FEP description. Disposition of the Primary FEPs provided below are sufficient to address Secondary FEPs. The screening decisions for significant Secondary FEPs are also provided in Section 7 of this document.

6.2.1 Tectonic Activity—Large Scale (1.2.01.01.00)

FEP Description: Large-scale tectonic activity includes regional uplift, subsidence, folding, mountain building, and other processes related to plate movements. These tectonic events and processes could affect repository performance by altering the physical and thermo-hydrologic properties of the geosphere.

Screening Decision: *Exclude*

Screening Decision Basis: Low Consequence

Screening Argument: Tectonic activity - Large Scale is *Exclude* from the TSPA based on low consequence.

Tectonic activity is an on going process. However, the tectonic processes that will occur in the Yucca Mountain region will have no significant impact on UZ or SZ flow and transport, waste-package integrity, or other components of the engineered barrier system (EBS). Therefore, there will be negligible impact on expected annual dose, and tectonic activity is therefore considered to be excluded based on low consequence.

Regional tectonic deformation proceeds at an almost imperceptible rate. The very slow contemporary strain rate in the Yucca Mountain area (<2 mm/yr) (Savage et al., 1999, p. 17627) is confirmed by paleoseismic slip rates calculated from fault displacement studies. These local slip rates are in the range of 0.001 - 0.03 mm/yr (*Characterize Framework for Seismicity and*

Structural Deformation of Yucca Mountain, Nevada ANL-CRW-GS-000003: CRWMS M&O 2000c, Table 6). Savage et al. (1999) present an evaluation of the strain accumulation rate at Yucca Mountain, Nevada for the period of 1983 to 1998, and address alternate interpretations indicating higher strain rates presented by Wernicke et al. (1998). Long-term deformation resulting from low strain rates includes uplift, subsidence, folding and regional tilting. The tectonic strain rate was evaluated as an uncertain parameter in the PSHA, and the uncertainty in the rate is reflected in the PSHA. The magnitude and rates of such deformation are insignificant with respect to the repository performance period (10,000 years) and with respect to perturbations caused by decay of the radioactive waste. Consequently, this FEP is *Exclude* based on low consequence.

The present tectonic regime of the Yucca Mountain region does not promote tectonic uplift. Because Yucca Mountain is in a presently waning extensional regime and flanks a basin, the likelihood of tectonic uplift is small. Any uplift of significance to a repository at Yucca Mountain could not develop within the next few million years. Therefore, uplift is *Exclude* based on low consequence.

Based on the history of the Crater Flat Basin as presented by Fridrich (1999), tectonic subsidence due to regional extension is a likely scenario at Yucca Mountain. However, the rate of subsidence has diminished consistently over the last several million years and the locus of subsidence-related extension has migrated west of Yucca Mountain (inferred from Fridrich 1999, p. 189; Dixon et al. 1995, p. 765). Given projected fault slip rates, subsidence-related effects at Yucca Mountain are *Exclude* based on low consequence during the period of interest.

The potential for tectonic changes to affect infiltration rates either by changing the orientation of tuff beds or by changing drainage patterns at the site are *Exclude* based on low consequence. A change in orientation of the tuff beds would most likely occur in the near vicinity of the faults and be expressed as hanging-wall rollover. Given the low normal-fault activity at Yucca Mountain and the small (less than 1.3 meter maximum along the Solitario Canyon) offsets per slip event, any increase in hanging-wall rollover to affect percolation flux through the tuff beds is extremely unlikely. It is more likely that fracture permeability will have a much greater influence on local flux rates than strata-confined matrix permeability that depends on the folding rate. For instance, changes in fracture aperture due to fault displacement have been shown to have insignificant effects on radionuclide transport through the UZ (*Fault Displacement Effects on Transport in the Unsaturated Zone*, ANL-NBS-HS-000020: CRWMS M&O 2000b, Section 7).

With regards to changes in drainage patterns and given the rapidity of stream-grade adjustment to climate change, percolation flux associated with drainage is not likely to be significantly influenced by rates of tectonic slope change or local base-level subsidence. Additionally, work performed for the TSPA-VA indicates that percolation flux is strongly dependent on rainfall (CRWMS M&O 1998c, Table 2-5 and Table 2-16), which is a function of climate change and independent of local tectonic processes. Because of the low rates of uplift and subsidence at Yucca Mountain during the repository performance period, tectonic-related changes will be insignificant relative to the percolation-flux effects of possible climate change. Therefore, FEPs related to tectonic-induced infiltration changes are *Exclude* based on low consequence.

Concerns that tectonic changes could induce local geothermal flux or convective flow in the saturated zone are also *Exclude* based on low consequence. Given the present tectonic state of Yucca Mountain and the present source of basaltic magma generation at depths of around 60 km (Crowe et al. 1995, Fig. 5-1), it is unlikely that localized effects will occur as a result of basaltic magma generation. The existing conditions also indicate that a significant (i.e., potentially hazardous) increase in geothermal gradient associated with tectonic activity would require several million years of evolution. Geothermal flux from tectonic activity is therefore *Exclude* based on low consequence.

Deformational processes associated with tectonism, however, can be punctuated by local events, such as earthquakes and volcanic eruptions, which are considered as disruptive events. Disruptive events are treated as separate and distinct FEPs in the following sections. Igneous events are specifically addressed in *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation,* ANL-WIS-MD-000017 (CRWMS M&O 2000d), and C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada,* ANL-MGR-GS-000001 (CRWMS M&O 2000e). Earthquake related events (due to ground motion and fault displacement) are specifically addressed in *Characterize Framework for Seismicity and Structural Deformation of Yucca Mountain, Nevada,* ANL-CRW-GS-000003 (CRWMS M&O, 2000g).

TSPA Disposition: Tectonic activity - Large Scale and the associated Secondary FEPs are *Exclude* from TSPA as described under the Screening Argument.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: None

Analysis and Discussion: Large-scale tectonic activity are interpreted for this FEP to refer to tectonism that is expressed at a regional scale (1:250,000 or less). Global- or plate-scale tectonics are unlikely to directly result in significant localized changes at Yucca Mountain, due to the distance to the plate margins and the great depth (about 60 km) to centers of basaltic magma generation.

Regional tectonic processes are manifested as patterns of systematic deformation that involve regional uplift, subsidence, folding, faulting, igneous activity, or any distinctive combination of such processes. In any given local area, such as Yucca Mountain, regional activity determines the style and recurrence of deformation expressed by local structure. Thus, the style and recurrence of fault slip at Yucca Mountain approximates the major effects of regional tectonic process that will be felt at Yucca Mountain probably for the next several tens or hundreds of thousands of years.

<ins>Tectonic Activity</ins>: Tectonic activity at regional scales typically is concentrated in zones or belts 10s to 100s of kms wide (Thatcher et al. 1999, pp. 1714 - 1715) and it persists for millions of years. At Yucca Mountain, tectonism is evolving westward through episodes of activity (inferred from Fridrich 1999, p. 191). Yucca Mountain is now about 50 km from the nearest

zones of significant present-day tectonic activity in the Great Basin. The significant tectonic zones include the eastern California shear zone, located west of the Funeral Mountains, and the intermountain seismic belt, located generally north of 37°N (Savage et al. 1995, p. 20260; Dixon et al. 1995, p. 765). These belts are characterized by high geodetic strain rates and recurrent earthquakes (Thatcher et al. 1999, pp. 1714 and 1715). In contrast, Yucca Mountain and its setting (i.e., the Crater Flat domain) have a low strain rate (Savage et al. 1999, p. 17627). The current loci of tectonic activity have moved west and north of Yucca Mountain (inferred from Fridrich 1999 p. 189; Dixon et al. 1995, p. 765).

Based on the geologic history of Yucca Mountain, tectonic changes would occur at rates that are infinitesimal with respect to the repository performance period, and the changes would be episodic. For example, creation of Yucca Mountain itself, including deposition of the tuff layers and block faulting, occurred over a period of about 2.5 to 3 M.y. (inferred from Fridrich 1999, p. 184 - 189; Sawyer et al. 1994, p. 1305). Episodic behavior in volcanic behavior is demonstrated by the quiescent period between deposition of the Timber Mountain Group and the Paintbrush Canyon Group alone - about 750,000 years (Sawyer et al. 1994, p. 1312). Furthermore, the rate of regional tectonism has decreased greatly since late Miocene (inferred from Fridrich et al. 1999).

Folding: "Folding, uplift or subsidence" as used in the FEPs descriptions refers to the effects of the tectonic processes of compression or extension. Regional compressive stresses that could produce uplift or depression related to subhorizontal (compressive) fold axes have not operated in the Yucca Mountain region or in the entire Great Basin within the past 50 M.y. (i.e., since Sevier orogeny) (inferred from Keefer and Fridrich 1996, pp. 1-12 to 1-13). Therefore the probability of compressional folding at Yucca Mountain during the repository performance period is negligible under the current tectonic regime.

Folding of the tuff beds, associated with extension at Yucca Mountain, is expressed chiefly as "rollover" (i.e., the anelastic behavior of the hanging wall proximal to the footwall) (Fridrich et al. 1996 p. 2-29). Rollover is a process that accompanies normal faulting of materials exhibiting low elastic strength; it requires repeated and significant displacement and sufficient hanging-wall fracturing to appreciably reduce elastic strength. Rollover is typically associated with increased fracturing as the block-bounding fault is approached. Additionally, rollover folds affect relatively small segments of the downthrown blocks. The rollover segments have been mapped and the repository design considers this feature. Folding due to rollover is possible, but at a rate governed by rates for fault slip at Yucca Mountain. The local cumulative slip rates are on the order of 0.01-0.03 mm/yr (*Characterize Framework for Seismicity and Structural Deformation of Yucca Mountain, Nevada* ANL-CRW-GS-000003: CRWMS M&O 2000c, Table 6). Within the last 12 M.y., rollover has led to a dip-steepening of lithologic units of about 20° (or about 1.6° per 1 million years). Any further rollover is expected to proceed at a rate less than or equal to the cumulative slip rate, resulting in a steepening of about 2° in a million years. Consequently, FEPs predicated on an assumption of folding during the performance period are *Exclude* from consideration based on low consequence.

The Secondary FEP 1.2.01.01.03,"Tectonic folding alters dip of tuff beds, changing percolation flux," (CRWMS M&O 1999b) is predicated on the assumption that dip constrains percolation flux and suggests that flux is controlled by strata-confined matrix permeability. The potential for increased permaeabilites caused hanging-wall fracturing far outweighs the significance of matrix permeability in rollover segments. It is more likely that fracture permeability will have a much greater influence on local flux rates than strata-confined matrix permeability that depends on folding rate. Assuming a critical angle of tilting of about 25° (Fridrich et al. 1996, p. 2-21 and 22), the tuff beds will likely fracture and slip before the change in orientiation of the tuff beds (i.e., an increase in fold-limb dip associated with rollover) becomes a significant factor in local percolation flux. Given the low, normal-fault activity at Yucca Mountain and the small offsets per slip event, any increase in hanging wall rollover that affects percolation flux is extremely unlikely. Because of the low dips involved, the very low folding rates (as expressed through local cumulative slip rates), and the significant influence of local fractures in local percolation flux, this FEP is *Exclude* based on low consequence. The effects of fractures on percolation flux are evaluated in the *Fault Displacement Effects on Transport in the Unsaturated Zone*, ANL-NBS-HS-000020 (CRWMS M&O 2000b).

<u>Uplift and Subsidence</u>: Uplift and subsidence associated with tectonic extension is an ongoing process in the Yucca Mountain region. The elevations of landforms (e.g., basins and ranges) in the Yucca Mountain region are a direct consequence of tectonic extension that has operated within the past 25 M.y. Ranges are loci of uplift or relative stability and basins are loci of chronic subsidence. For example, Bare Mountain, the range closest to Yucca Mountain, has undergone uplift within the 12-8 Ma interval (Hoisch et al. 1997, p. 2829). During that same period, the western part of Crater Flat basin subsided (inferred from Fridrich et al. 1999). Although rates of subsidence and uplift are presently very low, the spatial pattern of subsidence has not changed over time (inferred from Fridrich et al. 1999).

In this context, uplift is thought to result from either of two processes: magmatic inflation (Smith et al. 1998, Figure 2(B)) of the crust, or detachment faulting (Hoisch et al., 1997 p. 2829). Neither of these processes has affected Yucca Mountain directly, and neither process is thought to have been a factor in local deformation within the last 5 M.y. (inferred from Fridrich 1999, p. 190; Hoisch and Simpson 1993, p. 6822; Hoisch et al. 1997, p. 2829). Given the waning effect of extension (inferred from Fridrich 1999, p. 191; Dixon et al. 1995, p. 765) east of Death Valley and south of the intermountain seismic belt at around 37°N, significant uplift at Yucca Mountain is unlikely.

Tectonic subsidence is potentially significant to a future repository, as it is clear that recurrent block faulting at Yucca Mountain is a response to the widening and deepening of Crater Flat basin. The rate of subsidence approximates the cumulative rate of normal fault slip at Bare Mountain and Yucca Mountain. This local cumulative slip rate is low (0.001 - 0.03 mm/yr; *Characterize Framework for Seismicity and Structural Deformation of Yucca Mountain, Nevada* ANL-CRW-GS-000003: CRWMS M&O 2000c, Table 6), and subsidence will not perceptibly be advanced in the absence of slip along the block-bounding faults. Rate of subsidence of Crater Flat basin has diminished over time and the locus of subsidence has retreated to the southwest corner of the basin, away from Yucca Mountain (inferred from Fridrich 1999, p. 189). Because the repository block itself will not be significantly affected by present subsidence rates within a time frame of several million years, the FEPs predicated on an assumption of subsidence are *Exclude* based on low consequence.

Several of the Secondary FEPs assume uplift and subsidence as initiating mechanisms. These include: 1.2.01.01.01 "Folding, uplift, or subsidence lowers facility with regard to current water table"; and 1.2.01.01.05, 1.2.01.01.08, 1.2.01.01.09, 1.2.01.01.13, which all involve generic possible effects resulting from uplift and subsidence (see CRWMS M&O 1999b for Secondary FEPs). The general issues of folding, uplift, and subsidence are *Exclude* based on either low probability or low consequence; therefore, FEPs based on these assumptions are also *Exclude*. In the interest of specificity, however, the secondary FEPs are discussed in additional detail.

With regards to lowering of the repository elevation with respect to the current water table, three factors should be considered:

1) The local strain rate would need to be great enough that subsidence overtakes long-term changes in water-table elevation. The repository is roughly at the same elevation as Crater Flat and Jackass Flat. For the water table to intersect the repository due to tectonic changes, Crater Flat and Jackass Flats would have to become playas or areas of spring discharge. This is extremely unlikely because the horizontal geodetic strain rate in the Yucca Mountain region is <2 mm/yr (Savage et al., 1999, p. 17627, strain rate reported as nanostrain/yr), and regional strain patterns indicate waning effects of extension east of Death Valley (inferred from Fridrich 1999, p. 191). Consequently, regional groundwater flow will continue to be controlled by Death Valley and will not be interrupted by formation of local basins.

2) The vertical distance between the base of the repository and the saturated zone is approximately 300 meters. Excursions of the water table in Plio-Pleistocene time are estimated to be about 100 m or less (Stuckless 1996, pp. 98-99). Under long-term extension, normal faulting has caused the faulted blocks of Yucca Mountain to subside into Crater Flat basin. However, the rate of subsidence is proportional to the paleoseismic slip rate, amounting to no more than 30 m in one M.y. (i.e., the fault slip rate is 0.03 mm/yr through one million years). This is insignificant compared to distance separating the repository and the water table.

3) Elevation of the potentiometric surface is influenced by many factors including terrain relief, percolation, and base-level. Hence, wholesale inversion of topography is required for the repository to intersect the water table. Such an inversion would be tied to the paleoseismic strain rate and could only occur over a span of tens of million of years. The time spans required for tectonic uplift or subsidence to “lower” the repository with respect to the water table are orders of magnitudes greater than the repository performance period (10,000 years), and deformation effects are insignificant compared to climatically controlled changes in water table.

Secondary FEP 1.2.01.01.04 is listed as "Uplift or subsidence changes drainage at the site, increasing infiltration" (see CRWMS M&O 1999b). There are two principal controls on drainage development at Yucca Mountain: tectonic control (i.e., uplift and subsidence), which determines base level and regional slope; and climate, which determines stream-gradient adjustments and erosion/sediment transport rates. For purposes of this discussion regarding effects of tectonic processes, stratigraphic control and weathering are ignored.

Infiltration depends on how much water is fed directly to fractured bedrock, either through bare bedrock (hill crests) or through basal drainage of saturated colluvium/alluvium. Very high rainfalls produce channeled debris flows on colluvial slopes, indicating that these slopes shed water efficiently and are not reservoirs for percolation into bedrock. Given the rapidity of stream-grade adjustment to climate change (as represented by the presence of debris flows), percolation flux associated with tectonically-controlled changes in drainage are not likely to be significantly influenced by rates of tectonic-induced slope change or local base-level subsidence, and the changes in percolation flux are not likely to be distinguishable from changes in infiltration caused by climate change. This FEP is therefore *Exclude* based on low consequence.

Geothermal Effects: Yucca Mountain is located in an area of moderate heat flow in the southern Great Basin and lies south of the regions of relatively high crustal heat flow in the Great Basin that are thought to indicate latent tectonism (inferred from Lachenbruch and Sass 1978, pp. 212 and 246). The crust at Yucca Mountain has been cooling since final eruption of the Timber Mountain caldera, which deposited the uppermost volcanostratigraphic unit at Yucca Mountain about 11.4 Ma (Sawyer et al. 1994, Table 1). Formation of the caldera complex exhausted the late Miocene heat source, and the crust has been cooling steadily for the past 9 M.y. In Plio-Pleistocene time small batches of basalt have intruded the crust near Yucca Mountain from source depths at about 60 km (Crowe et al. 1995, pp. Fig 5.1). These observations can be interpreted to indicate a waning tectonic setting (Crowe et al. 1995, pp. 5-15 and 5-16).

Any change in regional strain rates at Yucca Mountain would likely be signaled by increased heat flux (inferred from Thatcher et al. 1999, p. 1717) and by a prolonged period of seismicity producing focal mechanisms at geometric variance from those that conform well to present fault patterns. Hypothetically then, tectonic activities could result in changes in geothermal conditions. This is addressed as the Secondary FEP 1.2.02.01.01 "Tectonic changes to local geothermal flux causes convective flow in SZ and elevates water table" (see CRWMS M&O 1999b).

An increase in geothermal gradient sufficient to lead to convective flow in the saturated zone would require extraordinary conditions. Some of these conditions, however, previously occurred in the 14-9 Ma interval to form the southwest Nevada volcanic field (inferred from Axen et al. 1993, pp. 69 and 70). The only way the existing geothermal gradient could be changed rapidly in the present tectonic setting, however, is to have a large volume of magma emplaced high in the mid-to-upper crust (approximately 5 km depth) (inferred from Lachenbruch and Sass 1978, pp. 224 and 244). This could bring the Yucca Mountain area to a pre-eruptive state with attendant hot-spring activity. However, this would require great extension rates and crustal mobility, a rapidly evolving mantle, and subcrustal conditions that involve either a mantle plume hot spot (Parsons et al. 1994, p. 83) or melting of weakened subducting slab (inferred from Bohannon and Parsons 1995, p. 957).

Given the present and foreseeable tectonic state of Yucca Mountain (slow rate of extension strain, minimal rate of subsidence) and the present source of basaltic magma generation at depths of around 60 km, a potential increase in geothermal gradient would require several million years of evolution. Consequently, this Secondary FEP is *Exclude* on the basis of low probability.

6.2.2 Fractures (1.2.02.01.00)

FEP Description: Groundwater flow in the Yucca Mountain region and transport of any released radionuclides may take place along fractures. Transmissive fractures may be existing, reactivated, or newly formed fractures. The rate of flow and the extent of transport in fractures is influenced by characteristics such as orientation, aperture, asperity, fracture length, connectivity, and the nature of any linings or infills. Generation of new fractures and reactivation of preexisting fractures may significantly change the flow and transport paths. Newly formed and reactivated fractures typically result from thermal, seismic, or tectonic events.

Screening Decision: *Include* for existing fracture characteristics; *Exclude* for changes of fracture characteristics.

Screening Decision Basis: *Include*: Meets Criteria / *Exclude*: Low Consequence

Screening Argument: Fractures and the associated Secondary FEPs for existing fracture characteristics are *Include* as described under the TSPA Disposition. Screening arguments for *Exclude* changes in fracture characteristics are also presented in the TSPA Disposition discussion.

TSPA Disposition: The existing fracture characteristics are included in the TSPA for both the UZ and SZ. The UZ flow portion of the TSPA will include scenarios based on the minimum, mean, and maximum fracture properties and will include the associated uncertainties. The approach to be used will be similar to that used for the TSPA-VA. The matrix and fracture-parameter values both for the hydrogeologic units and the faults were included in the base-case TSPA-VA UZ flow model (CRWMS M&O 1998c), and were included in the analysis performed in *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b). Fracture flow will be an explicit feature of the TSPA SZ flow-and-transport model. The SZ flow-and-transport model simulate saturated flow and advective transport through flowing intervals, which are a subset of water-conducting features within the fracture system (CRWMS M&O 1999e).

The present-day fracture system is directly included in the flow-and-transport models of the unsaturated zone in a manner similar to that presented by CRWMS M&O 1998c). The UZ model includes consideration of fracture data and uncertainty in calculations of flow and transport. Additionally, the effects of changes to the fracture system due to geologic effects on mountain-scale flow and radionuclide transport have been investigated using a sensitivity approach (*Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020: CRWMS M&O 2000b). The results indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture.

The SZ model also includes fractures and uncertainty in the hydraulic and transport properties of the fracture system (CRWMS M&O 1999e). Only some of the fractures within the saturated zone contribute to the flow. These contributing fractured zones are referred to as flowing intervals. The uncertainty in the existing flow system is represented in the model using stochastic simulations of the flowing intervals and of porosity, spacing of permeable fractures, longitudinal dispersivity, horizontal anisotropy, and colloid retardation. The SZ model assumes that future fracture systems will produce flowing intervals similar to the existing system. The re-location of the flowing intervals within each hydrologic unit does not affect the simulated contaminant flux at the 20 km boundary. As a result, the uncertainty represented in the existing model appears to capture the uncertainty in the future system. Future seismic activity would redistribute strain within the system. Redistribution of strain could open new fractures and close some existing fractures (Gauthier et al. 1996, p 163). As long as the resulting fracture system maintains the same orientation and general characteristics, however, there will be no net impact on the simulated contaminant transport.

Available analysis for the UZ and SZ flow models, as discussed above indicate that changes in the fractures would be of little significance and are therefore *Exclude.*

The probability of new fractures forming in intact rock is negligible. The PSHA (CRWMS M&O 1998b, p. 8-7 referring to intact rock (condition "d") at Points 7 and 8) indicate that the probability of a fracture (i.e., minimal displacement) developing in intact rock has less than a 10^{-8} annual exceedance probability. Consequently, the development of new fractures is of low probability. Unless stress vectors acting on Yucca Mountain were to deviate markedly from those acting within the past few million years, it is very unlikely that shear strength of intact rock will be exceeded in the presence of fracture sets favorably oriented to accommodate increased stress. Therefore, the formation of new fractures is *Exclude* based on low probability.

Therefore, the presence and effects of existing fractures and associated uncertainties are *Include*. The effects of changes to the fracture system are *Exclude* because of low consequence.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Probability Distribution for Flowing Interval Spacing* ANL-NBS-MD-000003 (CRWMS M&O 1999e)

Fault Displacement Effects on Transport in the Unsaturated Zone ANL-NBS-HS-000020 (CRWMS M&O 2000b)

Analysis and Discussion: Modeling and data reported by Ferrill, Winterle, et al. (1999, p. 1 and 4 and 5) strongly suggest that fractures exert significant control over groundwater flow at Yucca Mountain. Fractures could provide pathways for water infiltration into the repository and provide fast pathways for transmission of radionuclides to the accessible environment. Fracture-orientation distributions derived through Exploratory Studies Facility (ESF) mapping are very similar to distributions identified in surface mapping of individual lithostratigraphic units, indicating identical sample populations, thus implying fracture continuity from the surface of the mountain to the repository horizon.

The spacing, planar extent, and connectivity of fractures, however, varies considerably with the material properties and the thickness of each rock layer in the mountain; it is therefore impossible to form a simple generalization about fracture distribution or to predict hydrologic effects based on fracture patterns or fracture densities observed in any given layer. In addition to the gross spatial and geometric character of the fracture populations, specific features of each population are significant to hydrology, including aperture, asperities, and extent of secondary mineral lining.

The known characteristics of the fracture system have been incorporated into the UZ and SZ flow models for the TSPA, as stated above under the TSPA Disposition.

Fault and fracture dilation as a precursor to fault slip is theoretically possible, as is new fracturing during faulting or fracture reactivation. Such effects would be limited to areas of known faulting and could potentially enhance through-the-mountain water flow. The effect of changes to the fracture system due to geologic effects on mountain-scale flow and radionuclide transport have been investigated using a sensitivity approach (*Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020: CRWMS M&O 2000b). The effect of changes in fracture apertures was examined because several fracture properties (permeability, capillary pressure, and porosity) are a function of fracture aperture. The results indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture, and hence fracture dilation is of no significance.

The likelihood of new fractures forming in intact rock is very low. Unless stress vectors acting on Yucca Mountain were to deviate markedly from those acting within the past few million years, it is very unlikely that shear strength of intact rock will be exceeded in the presence of existing fracture sets favorably oriented to accommodate increased stress. The PSHA (CRWMS M&O 1998b, p. 8-7 referring to intact rock (condition "d") at Points 7 and 8) indicate that the probability of a fracture (i.e., minimal displacement) developing in intact rock has less than a 10^{-8} annual exceedance probability. Consequently, the development of new fractures is of low probability.

The effects and uncertainty associated with the existing fracture system are *Include* for the TSPA analysis, whereas effects due to future changes are *Exclude* based on low consequence.

6.2.3 Faulting (1.2.02.02.00)

FEP Description: Faulting may occur due to sudden major changes in the stress situation (e.g., seismic activity) or due to slow motions in the rock mass (e.g., tectonic activity). Movement along existing fractures and faults is more likely than the formation of new faults. Faulting may alter the rock permeability in the rock mass and alter or short-circuit the flow paths and flow distributions close to the repository and create new pathways through the repository. New faults or the reactivation of existing faults may enhance the groundwater flow, thus decreasing the transport times for potentially released radionuclides.

Screening Decision: *Include* for existing fault characteristics, *Exclude* for changes of fault characteristics.

Screening Decision Basis: *Include*: Meets Criteria / *Exclude*: Low Consequence

Screening Argument: Faulting FEPs for existing fault characteristics are *Include* as described under the TSPA Disposition. Screening arguments for *Exclude* changes in fault characteristics are also presented in the TSPA Disposition discussion.

TSPA Disposition: Fault characteristics (existing) will be incorporated in both the UZ and SZ Flow models being used for the TSPA. The UZ flow model will characterize the large-scale heterogeneities and geologic heterogeneities in the UZ at Yucca Mountain. It will incorporate many of the geologic complexities including stratigraphy, faults and associated offsets, dipping beds, and zones of alteration in a manner similar to that used for the TSPA-VA (CRWMS M&O 1998c, Section 2.4.3.1 and Figure 2-49). The matrix and fracture parameter values both for the hydrogeologic units and the faults were included in the base-case TSPA-VA UZ flow model (CRWMS M&O 1998c). The SZ flow model also incorporates the presence of existing faults through the inclusion of some of the faults as low-permeability zones (CRWMS M&O 1998d, Section 8.2.1.2) or as zones of enhanced permeability (CRWMS M&O 1998d, Section 8.5.2.2.3). Additionally, the impact of changes of fractures in fault zones has specifically been analyzed in *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b, Section 6.2.2.3).

Geologic studies and recurrent seismicity show, however, that faulting is an ongoing tectonic process at and near Yucca Mountain (Whitney 1996). Faulting is a disruptive process with potential effects that include earthquakes (i.e., vibratory ground motion), rock failure, and sudden changes in geometry and physical properties of rock adjacent to the fault that are relevant to hydrology and integrity of the potential repository.

Vibratory ground motions (seismicity) associated with faulting have been evaluated, and a detailed discussion is deferred to FEP 1.2.03.02.00, "Seismic vibration causes container failure" (see Section 6.2.6).

The potential for fault displacement to shear a waste container is discussed in FEP 1.2.02.03.00 (see Section 6.2.4) and is *Exclude* based on the low probability of the formation of new faults in intact rock and the requirement for set-backs from faults capable of displacements that have engineering significance, as discussed for the referenced FEP. Exclusion based on set-backs require asserting Assumptions 5.2 and 5.3. The impact of fault displacement on drift integrity is examined in *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GW-000004 (CRWMS M&O 2000f).

Faulting also is associated with changes in physical properties of adjacent rock that could be potentially relevant to hydrology. These related changes to hydrologic properties are addressed as noted for FEP No. 2.2.06.02.00, "Changes in stress (due to thermal, seismic, or tectonic effects) produce changes in permeability of faults" (see Section 6.2.20) and FEP No. 2.2.06.01.00, "Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock" (see Section 6.2.19). Both of these changes in stress conditions were considered in *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-

000020 (CRWMS M&O 2000b, Sections 6.2.2.2 and 6.2.2.3) through examining the sensitivity of radionuclide transport to change in fracture apertures in fault zones and on a mountain-wide scale. Changes in fracture apertures were examined because several fracture properties (permeability, capillary pressure, and porosity) are a function of fracture aperture. The analyses indicated that stress induced changes were of no significance.

Another aspect of faulting that could be important is the formation of new faults, particularly within the repository block. Figures 8-8 through 8-13 in CRWMS M&O (1998b) illustrate the probability of displacement on existing small faults and existing shear fractures. For the analysis represented by Figures 8-8 through 8-13, two points were selected at locations in the repository (Points 7 and 8 as indicated in the figures) to represent conditions observed inside the repository area. The points were assumed to represent various conditions that could occur within the repository area. These conditions included assumed existing cumulative displacements of 2 meters and 10 cm to represent existing small faults, and no displacement to represent shear fractures (or fractures with minimal movement). The mean 10^{-8} annual exceedance probability for these small faults and shear fractures is approximately 1 m, 10 cm, and <1 cm, respectively. The effects of reactivation, therefore, are covered by the range of aperture conditions presented in *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b, Section 6.2.2.3), as discussed above. With regard to the formation of new faults or fractures, the PSHA (CRWMS M&O 1998b, p. 8-7 referring to intact rock (condition “d”) at Points 7 and 8) indicates that the mean annual probability of a shear fracture (i.e., minimal displacement) developing in intact rock has less than a 10^{-8} annual exceedance probability. Consequently, the development of new faults and fractures is of low probability.

The characteristics of existing faults are included in the TSPA. The effects from reactivation of existing faulting are expected to be of low consequence, and the formation of new faults or fractures is of low probability. The effects of changes in faults are therefore determined to be *Exclude.*

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GW-000004 (CRWMS M&O 2000f).

Fault Displacement Effects on Transport in the Unsaturated Zone ANL-NBS-HS-000020 (CRWMS M&O 2000b)

Analysis and Discussion: Recurrent faulting is a tectonic process that will likely continue as discrete or distributed faulting during the repository performance period (10,000 years). Faulting is potentially significant because of its potential to compromise the structural integrity of the repository block and the potential to damage the engineered system and waste canisters.

<u>Fault Types and Mechanisms</u>: Several types of faulting exist at or in the vicinity of Yucca Mountain.

Dip/slip faulting refers to fault displacement directly along the dip of the fault plane and perpendicular to fault strike. Dip/slip faulting includes pure normal faulting (hanging wall down) or reverse faulting (hanging wall up). Most of the faulting at Yucca Mountain has a large component of dip slip and it is chiefly normal faulting, but some reverse faults have been identified (Day et al. 1998, pp. 8 and 12). Dip/slip faulting at Yucca Mountain could occur in the present extensional stress regime as pure normal faulting; most recently, active faults at Yucca Mountain (the block bounding faults) have a large component of dip slip or are essentially dip-slip faults. Fault-slip data for dip-slip faults have been analyzed and evaluated in the PSHA and are accounted for in both the fault-displacement and ground-motion hazard results (CRWMS M&O 1998b, Section 7 and 8).

Extensive work has been done in characterizing the faults present at Yucca Mountain and most of the following discussion is based on the compilation of work presented in Whitney (1996). Site characterization studies show that normal faulting (i.e., dip-slip faulting) is the predominant style of fault slip at Yucca Mountain (Fridrich et al. 1996, pp. 2-13 to 2-15). Normal faulting is known to have occurred at Yucca Mountain within the last 100 k.y. (Ramelli et al. 1996, Table 4.7.3) The block-bounding faults (e.g., Solitario Canyon fault and Bow Ridge fault) are normal faults, and minor intrablock faults, such as the Ghost Dance fault, are essentially normal faults (Day et al. 1996, pp. 2-1 to 2-9). These faults have been identified, mapped in detail, and their histories of Pleistocene/Holocene slip have been determined as part of the site characterization studies (Simonds et al. 1995, text from map; Day et al. 1998, pp. 4 and 8). Although slip rates are low and amount of offset per slip event is small, normal fault slip has recurred throughout the past several hundred thousand years at Yucca Mountain. The most active normal faults at Yucca Mountain have slip rates of about 0.03 mm/yr or less (*Characterize Framework for Seismicity and Structural Deformation of Yucca Mountain, Nevada* ANL-CRW-GS-000003 CRWMS M&O 2000c, Table 6) and slip recurrence intervals of around 20 k.y. or more. The low slip rates preclude exhumation of waste by faulting as suggested by Secondary FEP 1.2.02.02.17. Based on the average slip rate, the total displacement in 10,000 years will be approximately 0.3 meters, far less than the 300 m needed to result in direct exhumation.

Based on the findings of recent movement, it is likely that movement along existing normal faults will occur at Yucca Mountain during the repository performance period (10,000 years). The fault-slip data associated with normal faults at Yucca Mountain faults is analyzed and evaluated in the PSHA and is accounted for in the fault displacement analysis (CRWMS M&O 1998b, Section 8). As described above in the TSPA Disposition, existing faults are included in the TSPA.

Strike-slip faulting at Yucca Mountain is manifested chiefly as an oblique component to normal faulting. Strike-slip faulting, however, has occurred near Yucca Mountain and has been an important seismotectonic process in the Yucca Mountain region. Pure strike-slip faults are present at Yucca Mountain, chiefly along the Furnace Creek fault to the west and along the Rock Valley fault zone to the east (Whitney 1996, p. 4.13-4 and 4.13-5). Strike-slip faults are found north of the repository block (Day et al. 1998, p. 10). However, none of the strike-slip faults north of the repository has evidence of Pleistocene activity and even the amount of strike-slip offset is uncertain.

Toward the southern end of Yucca Mountain, an increasing component of strike-slip faulting has resulted in vertical axis rotation (rotation or bending of beds or layers around an inferred vertical axis as noted by variations in strike) (Rosenbaum et al. 1991, p. 1977; Minor et al. 1997, p. 32; inferred from Fridrich et al. 1999). Thus, toward the southern end of the mountain, fault slip becomes increasingly oblique and approaches strike-slip motion. However, faulting associated with vertical axis rotation (i.e., having a strong strike-slip component) is not known to have occurred at Yucca Mountain in Pleistocene time. Nevertheless, a minor component of strike slip is involved with normal-fault activity at Yucca Mountain, as determined by recent fault-plane mechanisms and by kinematic indicators (oblique slickenlines) on exposed fault planes (Day et al. 1996, p. 2-10). As described above in the TSPA Disposition, existing faults are included in the TSPA.

A variety of processes at Yucca Mountain, including normal faulting, vertical axis rotation, and basaltic volcanism, have been inferred by some to indicate the influence of a buried, episodically active, NNW-striking strike-slip fault (Schweickert and Lahren 1997, p. 25). There is no direct evidence of the existence of this fault, although a tectonic model for evolution of Crater Flat basin based on a buried strike-slip fault zone has been developed by Schweickert and Lahren (1997, p. 37). The inferred fault could be as much as 30 km long. The effects of an inferred buried strike-slip fault on ground-motion hazard at the proposed repository site are captured in the PSHA and the sensitivity of the analyses to strike-slip effects is minimal (CRWMS M&O 1998b, p. 7-22, Figures 7-27 to 7-29).

The succession of fault-tilted blocks that forms Yucca Mountain has also been attributed to detachment faulting (Scott 1990, p. 278; Ferrill et al. 1996, p. 2.6 and 2.7), and detachment faulting may have contributed to the formation of the present fault pattern at Yucca Mountain. Near Yucca Mountain, a detachment fault is exposed in the Funeral Mountains, and detachment faulting is interpreted to have created the Bullfrog Hills and to have occurred at Bare Mountain within the past 12 M.y. (Scott 1990, p. 278). This interpretation supposes that a detachment fault could be present at depths between about 5 km and 15 km, and that the block bounding faults at Yucca Mountain could flatten with depth and sole into the detachment fault (Ferrill et al. 1996, p. 2.6 and 2.7). Therefore, slip on the detachment could be transmitted up-dip as normal faulting at Yucca Mountain. However, a detachment faulting configuration for Yucca Mountain is purely conjectural. Geophysical data do not indicate a detachment beneath Crater Flat or Yucca Mountain, and local earthquakes indicate steeply-dipping planar fault mechanisms to depths as great as 11 km (Smith et al. 1995, p. 15). Regardless, the faulting hazard evaluation for Yucca Mountain (i.e., the PSHA) includes evaluations of the effects of alternative tectonic models, including the detachment model as a special case consideration (CRWMS M&O 1998b, p. 6-7). Because of its consideration in the PSHA and the resulting seismic and fault-displacement hazard curves, the presence of detachment faulting (Secondary FEP 1.2.02.02.09) is of low consequence to the TSPA and is therefore *Exclude*.

Fault -Displacement Evaluation: Considering the history of fault displacement and the proximity of faults to the projected Yucca Mountain repository, a probabilistic, fault-displacement hazard assessment was performed as part of the PSHA (CRWMS M&O 1998b, Section 8). This hazard was assessed at nine demonstration points, eight of which are within the repository block area. These nine points were selected to represent the expected ranges of fault-displacement-hazard conditions in terms of the types of features that have been encountered near or at the repository, including: 1) block-bounding, possibly seismogenic, faults with greater than 50 m cumulative displacement, 2) intrablock faults having a few to tens of meters of cumulative displacement, and 3) features observed within the ESF that are likely to be encountered within the proposed repository block ranging from small faults uncorrelated with surface features to intact rock. The following discussion describes the points chosen and the types of features represented.

1) Block-bounding faults, possibly seismogenic, with greater than 50 m cumulative displacement (Points 1 and 2)

Point 1 is a location on the Bow Ridge fault where it crosses the ESF. The Bow Ridge fault is a block-bounding fault that has been characterized by the expert teams as being a potentially seismogenic fault and/or to be part of a seismogenic fault system.

Point 2 is a location on the block-bounding Solitario Canyon fault, which has been characterized by the PSHA expert elicitation teams as one of the longer seismogenic faults within the Yucca Mountain site vicinity.

The Solitario Canyon fault and the Bow Ridge fault define the west and east sides of the repository block, respectively. These block-bounding faults at Yucca Mountain are normal faults that are controlled by deep crustal strain and slip every 10-30 k.y. Trench studies at Yucca Mountain have shown that the block-bounding faults have a history of Pleistocene slip (Menges and Whitney 1996, Section 4.2). Trench studies (Fridrich et al. 1996, p. 2-20) and analysis of regional stress and slip tendency at Yucca Mountain (Ferrill, Winterle et al. 1999, p. 4 and 5; Morris et al. 1996, p. 275) indicate that future fault slip will be confined to the block bounding faults.

Displacement along the Solitario Canyon fault is of primary concern for evaluating fault-displacement effects on the repository. The latest faulting documented near the repository block is along the Solitario Canyon fault, where the latest fracturing is dated as 15±1.6 ka (Ramelli et al. 1996, p. 4.7-43, Table 4.7.3). Two episodes account for most of the mid-to-late Quaternary offset along this fault, the largest of which occurred at 70-80 ka with as much as 130-cm displacement (Ramelli et al. 1996, p. 4.7-44, Table 4.7.3). Based on this Quaternary history, future faulting near the repository block is likely to display displacement on the order of 10 cm to 1 m (CRWMS M&O 1998b, Figure 8-3)

2) Intrablock faults having a few to tens of meters of cumulative displacement (Points 3, 4, and 5)

Point 3 is a location on the Drill Hole Wash fault where it crosses the ESF. Drill Hole Wash fault is one of the longer northwest-striking faults within the Yucca Mountain site vicinity.

Point 4 is a location on the Ghost Dance fault, which is one of the longer north-south intrablock faults within the controlled area

Point 5 is a location on the Sundance fault within the proposed repository footprint west of the ESF. The Sundance fault is an intermediate size, northwest-trending intrablock fault

Points 3, 4, and 5 are on mapped intrablock faults with north-south and northwest-southeast strikes, which, within the uncertainty of current understanding, may experience secondary displacement relative to primary displacement of block-bounding faults. Numerous intrablock faults, such as the Ghost Dance fault, are less confidently attributed to ongoing tectonism, and such faults do not seem to have been active in Pleistocene time (Taylor et al. 1996, Section 4.5.8 and 4.5.9). There is no evidence for Quaternary activity on the Ghost Dance and other minor faults near the repository (Taylor et al. 1996, Section 4.5.8 and 4.5.9).

The Drill Hole Wash fault is the closest example to a strike-slip fault in the near vicinity of the repository. However, interpretations of the character of this fault vary. The Drill Hole Wash fault was mapped as a dextral strike-slip fault by Scott and Bonk (1984, Map Sheet 1). Spengler and Rosenbaum (1980, p. 31) interpreted the buried fault strands as sinistral strike-slip, or oblique-slip faults.

3) Features observed within the ESF that are likely to be encountered with the proposed repository block ranging from small faults uncorrelated with surface features to intact rock (Points 7, 8, and 9)

Point 6 is a location on a small fault mapped in bedrock on the west side of Dune Wash. This point represents a location on one of the many small north-south-striking intrablock faults that have been mapped at the surface of Yucca Mountain.

Point 7 is a location approximately 100 m east of Solitario Canyon at the edge of the proposed repository footprint. Any one of four hypothetical conditions (a) through (d) below were considered to exist at this location and assessed. These conditions express features encountered within the ESF and not directly correlated with specific features observed at the surface. These conditions are as follows:

(a) A small fault having 2 m of cumulative displacement

(b) A shear having 10 cm of cumulative displacement

(c) A fracture having no measurable displacement (e.g., a shear fracture)

(d) Intact rock

Point 8 is a location within the proposed repository footprint midway between the Solitario Canyon and Ghost Dance faults. The same four conditions described at Point 7 were considered to exist at this location.

Point 9 is a location on in Midway Valley east of the Bow Ridge fault on an observed fracture having no displacement in Quaternary alluvium.

The mean hazard results for fault displacement at the nine points are provided in the PSHA (CRWMS M&O 1998b, Figures 8-2 through 8-14). The hazard results at all locations have large uncertainties.

With the exception of Points 1 and 2, both of which are on primary block-bounding faults, the mean displacement value is <0.1 cm, with 10^{-5} annual exceedance probability. The fault-displacement values for annual exceedance probabilities less than 10^{-6} begin to exhibit increasing uncertainty. At 10^{-8} annual exceedance probability, the mean displacement hazard for Points 3, 4, 5, and 6 and for the assumed condition of 2-m displacement at Points 7 and 8 are approximately 1 to 2 m. Further, the 15th fractile curves indicate displacement as low as 2 cm in at least one instance. Based on the PSHA results (CRWMS M&O 1998b, Figures 8-8 through 8-14) the probability of new fault movements along small faults (with cumulative displacements of 2 meters or less) is less than 10^{-4} in 10,000 years, based on a 10^{-8} annual exceedance probability (See Assumption 5.4). For existing fractures with no measurable displacement (as represented by Points 7 and 8 for condition "c" discussed above), the 10^{-8} annual exceedance probabilities indicate displacements of no larger than 10 cm and as little as 0.5 cm (CRWMS M&O 1998b, Figures 8-9 and 8-13). Displacement effects are likely to be of no consequence and can be considered as *Exclude* when coupled with the analysis from *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b, Section 7).

With regard to the formation of new faults or fractures, the PSHA (CRWMS M&O 1998b, p. 8-7 referring to intact rock (condition “d”) at Points 7 and 8) indicate that the probability of a shear fracture (no displacement) developing in intact rock has less than a 10^{-8} mean annual exceedance probability. Consequently, the development of new faults and fractures is of low probability. Therefore, the effects of new faults are *Exclude* from TSPA.

The DOE Topical Report, *Preclosure Seismic Design Methodology for a Geologic Repository at Yucca Mountain, Nevada*, Topical Report YMP/TR-003-NP, REV 2 (YMP 1997), describes the criteria to be used to address faults with regard to the repository seismic design. The primary method will be fault avoidance to the extent reasonably achievable by layout of the repository and placement of the drifts. The report also stipulates that postclosure design requirements will be assessed through a systems evaluation. The more stringent of the preclosure and postclosure requirements will govern the design.

The NRC provides guidance for fault displacement design criteria in NUREG-1494, *Staff Technical Position on Consideration of Fault Displacement Hazards in Geologic Repository Design* (McConnell and Lee 1994, p. 4). This guidance recommends that Type I faults within the geologic repository operations area be avoided when reasonably achievable. Type I faults are defined in NUREG-1451, *Staff Technical Position on Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository* (McConnell et al. 1992, p. 5), as faults or fault zones that are subject to displacement and are of sufficient length and location such that they may affect repository design or performance. NUREG-1494 recommends fault avoidance but explicitly recognizes that fault avoidance may not be possible for all repository structures, especially drifts.

Applicable criteria for fault set-back for preclosure design of the facility have been developed (CRWMS M&O 1998a, Section 1.2.1.7 and Section 1.2.1.8), and will be applied to existing faults with known or suspect Quaternary-age displacements.

- A minimum set-back distance of 60 m shall be accommodated from the closest edge of the repository openings to the main trace of the fault zone (CRWMS M&O 1998a, Section 1.2.1.7).

- A 15 m set-back of waste packages from faults and a 5 m set-back of waste packages from splays associated with faults shall be accommodated by emplacement drifts (CRWMS M&O 1998a, Section 1.2.1.8).

- Fault displacement of less than 1 cm is considered insignificant with respect to the repository design (*Ground Control System Description Document,* CRWMS M&O 1998e, BCA000000-01717-1705-00011, Section 1.2.2.1.4).

Analyses to determine the effects of fault displacement on emplacement drifts, the drip shield, backfill, and the waste package have also been performed in *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GW-000004 (CRWMS M&O 2000f). Primary fault displacements ranging from 0.1 cm to 100 cm were analyzed. This range of displacements roughly approximates the 10^{-8} annual exceedance probability for all nine points (i.e, Point 1 through 9 described previously) evaluated in the PSHA, except for Points 1 and 2 (CRWMS M&O, 1998b, Figs 8-2 through 8-14). A displacement of 100 cm (or 1 m) roughly corresponds to the maximum measured Quaternary displacement on the Solitario Canyon fault (Ramelli et al. 1996, Table 4.7.3).

With the use of set-backs, shear stresses induced on the drip shield and waste packages by fault-displacement hazards will be mitigated either with or without the engineered backfill (*Effects of Fault Displacement of Emplacement Drift* ANL-EBS-GE-000004 (CRWMS M&O 2000f, Section 6.5.2 and 6.5.3)). This conclusion presumes that the fault does not intersect the emplacement drift. Even without the backfill, the gap between the drip shield and the emplacement drift should be adequate to accommodate the effects of displacement over the range of displacements considered. Rotation and distortion of drip shields or waste packages may occur where the fault intersects the invert below the drip shield or waste package. However, CRWMS M&O (1998a Sections 1.2.1.7 and 1.2.1.8) requires set-backs from faults, so this aspect of unacceptable performance can be excluded on the basis of low consequence with the assertion of Assumption 5.2 and 5.3).

Displacement hazards corresponding to preclosure design events (10^{-5} annual exceedance probability) are negligible for the intrablock faults (Drill Hole Wash, Ghost Dance, and Sundance faults) represented by Points 3, 4, and 5, as well as for the secondary fault and fracture conditions represented by Points 6, 7, and 8. Using a set-back of 60 meters from the Solitario Canyon and Bow Ridge primary block-bounding faults, shear stresses induced by fault displacements corresponding to the preclosure design event are negligible.

These results can be extrapolated to fault displacement hazards corresponding to the recurrence frequency of 10^{-4} in 10,000 years, the target probability established in DOE's Interim Guidance (Dyer 1999) for excluding events from performance assessment.

It is concluded that fault displacement is *Exclude* based directly on negligibly low probability (for secondary faults and features: Points 6, 7, and 8), or mitigated by appropriate set-back for primary block-bounding faults (Points 1 and 2) and intrablock faulting (Points 3, 4, and 5). This FEP is therefore *Exclude* based on low consequence.

Growth and Reactivation of Faults: Recurrent faulting is a significant tectonic process that will likely continue as discrete or distributed faulting during the repository performance period at Yucca Mountain.

With regards to processes creating new faults and/or reactivating existing faults, the tectonic history of Yucca Mountain indicates a great decrease in extension during the last few million years (inferred from Fridrich et al. 1999). Additionally, there is a low local cumulative slip rate of faults active during the Pleistocene (0.001 - 0.03 mm/yr: *Characterize Framework for Seismicity and Structural Deformation of Yucca Mountain, Nevada* ANL-CRW-GS-000003 CRWMS M&O 2000c, Table 6), and there is an apparent stability of ancient intrablock faults. Furthermore, *in situ* stress measurements (Stock et al. 1985, Table 1) and analyses of slip tendency (Ferrill, Winterle, et al. 1999, p. 4 and 5, Stock et al. 1985, p. 8705) indicate that the block-bounding faults are likely to slip under an increased stress load. Given these conditions, it is very unlikely that new faults will form in an environment where old faults are favorably oriented in the present stress field and are highly likely to slip.

Activation of a new fault strand has been addressed in the PSHA and shown to be of low probability. The effects are captured in the probabilistic fault displacement and ground-motion hazard results provided in the PSHA (CRWMS M&O 1998b, Sections 7 and 8). Activation of a new fault strand could theoretically occur by propagation of a fracture tip, a fault splay, or a blind fault extending from an existing fault segment (as opposed to formation of an entirely new fault). This is possible because tensile stress and shear stresses tend to be concentrated at fault or fracture tips (Segall and Pollard 1983, p. 567). Changes in stress at a fault tip during an earthquake could propagate fractures some distance into intact rock, especially if preexisting, aligned fractures meet each other. Although the important fault strands having a history of Pleistocene activity are mapped, blind fault splays oriented toward the repository block may exist at depth. It is also remotely possible that basaltic intrusion could propagate a new fault strand of local extent. However, given the strain rate and fault-slip recurrence rate at Yucca Mountain, it is unlikely that significant, new, fault-strand activation will occur during the repository performance period.

The possibility of new faulting and shear fracturing was evaluated in the PSHA. With regard to the formation of new faults or fractures, the PSHA (CRWMS M&O 1998b, p. 8-7 referring to intact rock (condition "d") at Points 7 and 8) indicates that the probability of a shear fracture (no displacement) developing in intact rock internal to the repository has less than a 10^{-8} annual exceedance probability. Consequently, the development of new faults and fractures or activation of new fault strands is of low probability and is determined to be *Exclude.*

The reactivation of old fault strands has also been evaluated in the PSHA and incorporated into the seismic and fault-displacement hazard curves presented in the PSHA (CRWMS M&O, 1998b, Sections 7 and 8). Possible fault linkages were evaluated in the PSHA for the Yucca Mountain site, through the consideration of distributed-faulting and multiple-rupture scenarios. The effects of fault linkages and relay faults are captured in the probabilistic fault-displacement and ground-motion hazard results presented in the PSHA (CRWMS M&O 1998b, Section 6.4).

Further consideration in the TSPA is therefore excluded on the basis of low consequence. Block-bounding faults at Yucca Mountain consist of discrete breaks, several km long, called segments or strands, that are linked together by short, complex relay faults (Ferrill, Stamatakos, et al. 1999, p. 1033). An old fault strand at Yucca Mountain could theoretically be reactivated as a result of static stress or earthquake triggering. A large earthquake could break two or more linked strands (Ferrill, Stamatakos, et al. 1999, p. 1033), but a relatively small earthquake is more likely to activate one or part of a single strand. This typically is the style of activation of range-front faults in the Great Basin. It is likely that any future slip on block-bounding faults at Yucca Mountain will involve partial or full reactivation of an old fault strand. This style of reactivition was included in the PSHA evaluations as described above.

CRWMS M&O (1998b, Figures 8-8 through 8-13) provides the probability of additional displacement along existing small faults and existing shear fractures (i.e., with existing cumulative displacements of 2 meters and 10 cm for small faults, and no displacement at shear fractures). The mean 10^{-8} annual exceedance probability for these small faults and shear fractures (as represented in the PSHA for Points 7 and 8, as described previously) is approximately 1 m, 10 cm, and <1 cm, respectively. Therefore, the effects of reactivation are covered by the range of aperture conditions presented in *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b, Section 7) as discussed in the TSPA Disposition above. Reactivation of old fault strands is therefore *Exclude* based on low consequence.

6.2.4 Fault Movement Shears Waste Container (1.2.02.03.00)

FEP Description: Fault slip could partially or completely offset one or more tunnels in the repository, thereby shearing any waste containers that lie across the fault plane.

Screening Decision: *Exclude*

Screening Decision Basis: Low Probability

Screening Argument: The history of faulting and the nature of fault slip and its structural effects at Yucca Mountain are well known (CRWMS M&O 1998b; Whitney 1996) *In situ* stress measurements indicate that faults at Yucca Mountain are weak and at the point of failure (Stock and Healey 1988, p. 92, Stock et al. 1985, p. 8705). As discussed in the following paragraph, under the present stress regime there is only a negligible probability that new faults will break unfaulted rock. Rather, faults having a history of Quaternary activity will slip. Consequently, there is a low probability of intrablock fault activity or of new faulting in the repository block (see FEP 1.2.02.02.00 Faulting).

CRWMS M&O (1998b, Figures 8-8 through 8-13) provides the probability of additional displacement along existing small faults and existing shear fractures (i.e., with assumed existing cumulative displacements of 2 meters and 10 cm for small faults, and no displacement at shear fractures). These features are representative of conditions likely to be found in the repository area (as represented in the PSHA for Points 7 and 8, as described in Section 6.2.3). The mean 10^{-8} annual exceedance probability for these small faults and shear fractures is approximately 1 m, 10 cm, and <1 cm, respectively. Therefore, the potential for displacements to shear waste containers is expected to be minimal, even if the fault were to directly intersect the drift, and no allowance for offsets from faults was considered.

Analyses to determine the effects of fault displacement on emplacement drifts, the drip shield, backfill, and the waste package have also been performed in *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GW-000004 (CRWMS M&O 2000f). Primary fault displacements ranging from 0.1 cm to 100 cm were analyzed. This range of displacements roughly approximates the 10^{-8} annual exceedance probability for all nine Points evaluated in the PSHA, except for Points 1 and 2 (CRWMS M&O, 1998b, Figs 8-2 through 8-14). A displacement of 100 cm (or 1 m) roughly corresponds to the maximum measured Quaternary per-event displacement on the Solitario Canyon fault (Point 1).

With the use of set-backs (see Assumptions 5.2 and 5.3), shear stresses induced on the drip shield and waste packages by fault-displacement hazards will be mitigated with or without the use of engineered backfill (*Fault Displacement Effects on Emplacement Drift* ANL-EBS-GE-000004: CRWMS M&O 2000f, Sections 6.5.2 and 6.5.3). This conclusion presumes that the fault does not intersect the emplacement drift. Even without the backfill, the gap between the drip shield and the emplacement drift should be adequate to accommodate the effects of displacement over the range of displacements considered. Rotation and distortion of drip shields or waste packages could potentially occur where the fault intersects the invert below the drip shield or waste package. However, this condition can be eliminated with the use of set-backs, which are part of the design basis.

Given the known behavior of faults at Yucca Mountain, the fact that they represent a spatially fixed hazard that can be mitigated by repository layout and engineering design, and based on the low probability of intrablock fault activity or of new faulting in the repository block, this FEP is *Exclude* on the basis of low probability.

TSPA Disposition: Fault movement shears waste containers is *Exclude*, based on low probability as discussed in the Screening Argument.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GW-000004 (CRWMS M&O 2000f).

Analysis and Discussion: It is appropriate to think of the block-bounding faults as weak links. They will fail and focus strain effects, thereby preventing significant damage to the larger repository block volume. *In situ* stress measurements indicate that faults at Yucca Mountain are weak and at the point of failure (Stock and Healey 1988, p. 92, Stock et al. 1985, p. 8705). Therefore, under the present stress regime, new faults will not break unfaulted rock; rather, faults having a history of Quaternary activity will slip. The location of faults with Quaternary movement has been an extensive and on-going effort in the repository area. Given that the fault traces will be observable during repository constructions (as they have been in the ESF and Cross-Drift), adequate offset from and avoidance of the faults can be incorporated into waste emplacement design.

The following applicable criteria for fault set-back for preclosure design of the facility have been developed (CRWMS M&O 1998a, Sections 1.2.1.7 and 1.2.1.8).

- A minimum set-back distance of 60 m shall be accommodated from the closest edge of the repository openings to the main trace of fault zones (CRWMS M&O 1998a, Section 1.2.1.7).

- A 15-m set-back of waste packages from faults and a 5-m set-back of waste packages from splays associated with faults shall be accommodated by emplacement drifts (CRWMS M&O 1998a, Section 1.2.1.8).

6.2.5 Seismic Activity (1.2.03.01.00)

FEP Description: Seismic activity (i.e., earthquakes) could produce jointed-rock motion, rapid fault growth, slow fault growth, or new fault formation, resulting in changes in hydraulic heads, changes in groundwater recharge or discharge zones, changes in rock stress, and severe disruption of the drifts (e.g., vibration damage, rockfall).

Screening Decision: *Exclude* for indirect effects / Exclude TBV for waste package / *Include* for drip shield damage and cladding damage.

Screening Decision Basis: *Exclude and Exclude* TBV: Low Consequence / *Include*: Meets Criteria.

Screening Argument: Seismic Effects, as described above, are considered as *Exclude* from the TSPA. With the exception of drip shield and cladding damage, seismic effects are not directly included in the TSPA efforts and in many specific instances have been directly excluded by other seismic related FEPs, typically on the basis of low consequence. Consequently, "Seismic Effects" are *Exclude* for indirect effects.

However, seismic effects have been considered in preclosure design criteria and are reflected in repository component design parameters (such as required set-backs from faults and system component performance requirements based on the seismic criteria specified in Dyer 1999). These criteria are reflected in the repository design being used in the TSPA. Seismic effects are being addressed by considering effects on parameters (such as increased corrosion) resulting from damage to the drip shields and seismic-induced damage to fuel-rod cladding. These effects are included in the TSPA in terms of package performance parameters.

Seismic effects are addressed by multiple, more specific FEPs. As summarized below, individual issues identified in this broadly-worded FEP are addressed in the context of more specific FEPs.

Seismically-induced rockfall and drift degradation (as it relates to severe disruption of drifts) and jointed-rock motion are *Exclude* as addressed in FEP 2.1.07.01.00, "Rockfall" and in FEP 2.1.07.02.00, "Mechanical degradation or collapse of drift." These FEPs are *Exclude*.

Fault growth is addressed in FEP 1.2.02.02.00, "Faulting" as a change in fault parameters, and is *Exclude*.

Effects of the displacement of faults is addressed in FEP 1.2.02.03.00, "Fault movement shears waste container," which is *Exclude.*

Seismic effects on the drip shield, fuel-rod cladding, and waste package are discussed in FEP 1.2.03.02.00, "Seismic vibration causes container failure." Although not yet demonstrated, it is unlikely that seismic vibration will cause waste package failure. Accordingly, it is considered as *Exclude* TBV for the waste package and *Include* for the drip shield and fuel-rod cladding.

Seismic effects on groundwater flow are addressed in FEP 1.2.10.01.00, "Hydrologic response to seismic activity," which is also *Exclude.*

Effects of changes in rock stress are addressed in FEPs 2.2.06.01.00, "Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock," 2.2.06.02.00, "Changes in stress (due to thermal, seismic, or tectonic effects) produce changes in permeability of faults," and 2.2.06.03.00, "Changes in stress (due to seismic or tectonic effects) alter perched water zones." All of these FEPs are *Exclude*, based on low consequence.

TSPA Disposition: Seismic Effects, as described above, are considered as *Exclude,* based on low consequence. *Exclude* for indirect effects / Exclude TBV for waste package / *Include* for drip shield damage and cladding damage.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Characterize Framework for Seismicity and Structural Deformation of Yucca Mountain, Nevada* ANL-CRW-GS-000003 (CRWMS M&O 2000c)

Analysis and Discussion: The proposed repository is expected to experience repeated vibratory ground motion from periodic earthquake occurrences in the region of the site. This process of repeated ground motion has been quantified in the PSHA (CRWMS M&O 1998b, Section 7). Probabilistic seismic hazard results were obtained by integrating over all variables of the seismic environment. These variables included seismic sources, earthquake recurrence distribution, and estimation of ground motion. The analysis also incorporated any associated variability and uncertainty. Thus, the ground-motion hazard results provide statistically robust ground motions that have been used to evaluate stresses imposed on repository drifts, the EBS, and directly on the waste container.

6.2.6 Seismic Vibration Causes Container Failure (1.2.03.02.00)

FEP Description: Seismic activity causes repeated vibration of container and/or container-rock wall contact, damaging the container and its contents.

Screening Decision: *Exclude*, TBV for waste package / *Include* for drip shield and fuel-rod cladding

Screening Decision Basis: *Exclude*: Low Consequence / *Include*: Meets Criteria

Screening Argument: For purposes of the screening of this FEP, it is assumed (see Assumption 5.4) that the definition of the probability criterion of $10^{-4}/10^{4}$ yr refers to the probability of unacceptable performance, which is the product of the hazard level (e.g., ground motion) and the consequences (e.g., damage to the drip shield). It is also assumed that backfill and drip shields are included in the repository design (see Assumptions 5.2 and 5.3).

For purposes of this FEP, the container is being broadly defined to include the drip shield, the waste package (i.e., the shell around the basket and the fuel rods), and the fuel-rod cladding. Seismic damage to the drip shields (via joint separation) and to the fuel-rod cladding are *Include* in the TSPA.

Current preclosure waste-package performance criteria require that the waste-package performance be based on the 10^{-4}/yr ground-motion spectra, suggesting that no significant damage from ground motion is likely to occur until the design ground motion is exceeded. Based on Figures 7-4 and 7-10 from the PSHA (CRWMS M&O 1998b), the peak ground acceleration for a 10^{-4} annual exceedance probability ground-motion event will be less than 0.6 g. The mean 10^{-8} annual exceedance probability peak accelerations would be on the order of 1 g or greater.

An analysis of the effect of ground motion on breakage of commercial spent-nuclear-fuel cladding is provided in the Calculation*, Breakage of Commercial Spent Nuclear Fuel Cladding by Mechanical Loading* CAL-EBS-MD-000001 (CRWMS M&O 1999f). The analysis shows that ground-motion levels up to a 10^{-6} annual exceedance probability are insufficient to cause any fuel rods to rupture. Because a low probability ($\leq 10^{-8}$ annual exceedance probability) has not been established, seismic-induced fuel-rod cladding damage is *Include* for the TSPA.

Assuming a 10^{-4} annual exceedance probability threshold, the probability of damage leading to a significant release from the waste package should be shown to be as low as 10^{-4}/yr (i.e., product of the probability of the triggering motion occuring and the probability of unacceptable damage) for the FEP to be excluded based on the basis of low probability. There are several design factors that suggest, but do not currently define, a low probability of damage including that the waste package is protected from rockfall by the backfill and drip shield; the waste package is protected from rolling by the emplacement pallet design; and the waste package has a low center of gravity. Furthermore, the individual waste packages are relatively short and can move independently from each other during ground motion.

A second consideration is whether damage to the waste package would result in a significant increase in release of radionuclides through time, compared to other waste-package release mechanisms currently included in the TSPA. The TSPA currently includes the effects of seismic damage as it pertains to increased corrosion of the waste packages stemming from drip-shield joint separation. Degradation of the waste containers is being evaluated through the WAPDEG analysis (in progress), which focuses on the protection afforded to the waste package by the drip shield. Damage impacts are evaluated by varying the amount of moisture reaching the waste-package surface. However, drip shields or waste packages damaged by ground motion will be of little or no consequence unless they are located below a drip in the emplacement drift. Even so, some waste-package corrosion will occur in the humid environment under the intact drip shields, so some waste-package failures will eventually occur even without drip-shield damage. Additionally, the TSPA will include provisions for damage of fuel-rod cladding.

Based on the current consideration of ground motions in the design of the waste packages, factors suggesting a low probability of occurrence of significant damage, and the existing consideration of other seismically-induced effects, it is likely that waste package failure can be *Exclude* on either low consequence or possibly as low probability. This screening argument, however, is qualitative in nature and requires verification. Consequently, the waste package aspect of this FEP is *Exclude* TBV. Damage to the drip shield and fuel-rod cladding are *Include*.

TSPA Disposition: Seismic Vibration Causes Container Failure is *Exclude* TBV for the waste package as described in the Screening Argument. It is *Include* for the drip shield and for fuel-rod cladding also as described in the Screening Argument.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Characterize Framework for Seismicity and Structural Deformation of Yucca Mountain, Nevada* ANL-CRW-GS-000003 (CRWMS M&O 2000c)

Analysis and Discussion: This FEP is predicated on the assumption that ground motion produced by the occurrence of earthquakes in the Yucca Mountain region could damage or result in failure of the EBS or waste package or could directly damage the fuel-rod cladding. Similarly, ground motions could trigger rockfall in the repository drifts thereby damaging or causing the EBS to fail (FEP No. 2.1.07.01.00). Evaluation of this analysis requires consideration of Assumptions 5.1, 5.2, 5.3, and 5.4 as described in Section 5 of this document.

The proposed repository is expected to experience repeated vibratory ground motion from periodic earthquake occurrences in the region of the site. This process of repeated ground motion has been quantified in the PSHA (CRWMS M&O 1998b, Section 7). Probabilistic seismic hazard results are obtained by integrating over all variables of the seismic environment. These variables include seismic sources, earthquake recurrence distribution, and estimation of ground motion. The PSHA specifically incorporates the variability and uncertainty in these variables (CRWMS M&O 1998b, Section 7.1.1). Thus, the ground-motion hazard results provide statistically robust ground motions that may be used to evaluate stresses imposed on repository drifts, the EBS, and directly on the waste container. Ground-motion hazard curves are contained in CRWMS M&O (1998b, Section 7, Figures 7-4 through 7-14).

The waste package comprises several components including spent nuclear fuel and basket, fuel-rod cladding, and the shell round the basket and fuel rods. The current repository design also includes installation of a drip shield (to protect the waste package from dripping water) and backfill. Vibratory ground motion will induce stresses in the drip shield and waste container during the repository-performance period. The DOE Topical Report (YMP 1997) directs that these components be designed for ground motion having 10^{-4}/yr frequency of occurrence to meet preclosure radiological-safety performance.

The TSPA currently includes the effects of seismic damage as it pertains to increased corrosion of the waste packages stemming from drip-shield joint separation. Degradation of the waste containers is being evaluated through the WAPDEG analysis (in progress), which focuses on the protection afforded to the waste package by the drip shield. The damage effects are evaluated by varying the potential for moisture to reach the waste-package surface.

The various parameters in the WAPDEG analysis include multiple factors. Water is not uniformly distributed in the subsurface, rather in the ESF it is observed to occur in widely spaced seeps due to its preferred flow through fractures, which have a range of properties and spacings (see discussions in *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b). Consequently, even drip shields or waste packages damaged by ground motion will be of little or no consequence unless they are located below a seep in the emplacement drift. Even so, some waste-package corrosion will occur in the humid environment under the intact drip shields, so some waste-package failures will eventually occur even without drip-shield damage. Additionally, drip shields that are located beneath seeps will degrade differently than those in drier portions of the repository. Finally, waste packages that are under drip shields that are beneath seeps will eventually be affected by the water and subsequent corrosion of the waste package will occur with or without ground-motion damage. WAPDEG captures all of these considerations.

An analysis of the effects of ground motion on drift degradation or collapse is provided in *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a) and the FEP Screening Argument is provided in FEP No. 2.1.07.01.00. As discussed in this screening argument, the LADS design for the proposed repository is Enhanced Design Alternative II, which includes a drip shield and backfill (CRWMS M&O 1999d, p. 4-16 and 4-17). Based on the *Drift Degradation Analyses* (CRWMS M&O 2000a), it was concluded that the presence of these engineered features precludes mechanical degradation or failure of the waste container by rockfall in the repository drifts. Thus, waste-container failure caused by rockfall in the repository drifts is *Exclude*.

In the current design, the waste package is protected from rockfall by the backfill and drip shield. It is protected from rolling by the emplacement pallet design and its low center of gravity in the drift. Also, the individual waste packages are relatively short and can move independently from other waste packages during ground motion. Qualitative reasoning based on the current design suggests that ground-motion damage to the canister will eventually be *Exclude*. However, this is a qualitative argument that needs verification. Furthermore, YMP (1997) requires postclosure design considerations to be determined by means of a systems analysis. Should the analysis conclude that a more stringent seismic design is required to meet postclosure performance objectives, the components will be designed to meet the more stringent requirements. Failure of the EBS and waste containers due to loads induced directly by ground motion are therefore *Exclude* TBV, pending completion of analyses of these components.

6.2.7 Seismicity Associated with Igneous Activity (1.2.03.03.00)

FEP Description: Seismicity associated with future igneous activity in the Yucca Mountain region may affect repository performance

Screening Decision: *Exclude* for most effects / *Include* for damage to drip shields and fuel-rod cladding.

Screening Decision Basis: *Exclude*: Low Consequence / *Include*: Meets Criteria

Screening Argument: Seismicity related to volcanic processes, particularly basaltic volcanoes and dike injection, was explicitly modeled in volcanic source zones by only two of the six expert teams working on the PSHA (*Characterize Framework for Seismicity and Structural Deformation of Yucca Mountain, Nevada* ANL-CRW-GS-000003 CRWMS M&O 2000c, Section 4.1.2.3). Volcanic-related earthquakes were not modeled as a separate source zone by the four other PSHA expert teams, under the assumption that, because of the low magnitude and frequency of volcanic-related seismicity, they were accounted for by the areal, source-zone evaluation. Because the effects are included in the PSHA evaluations, seismic activity due to igneous activity is treated in the TSPA identically as general seismic activity (Section 6.2.5): indirect effects are *Exclude* based on low consequence. Damage to drip shields and fuel-rod cladding are *Include*.

TSPA Disposition: "Seismicity Associated with Igneous Activity" is *Exclude/Include* as described under the Screening Argument

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Characterize Framework for Seismicity and Structural Deformation of Yucca Mountain, Nevada* ANL-CRW-GS-000003 (CRWMS M&O 2000c)

Analysis and Discussion: Volcanic eruption commonly is preceded and accompanied by swarms of earthquakes that indicate progressive rock failure as magma migrates to the Earth's surface (Smith et al. 1998, p. 158). At Yucca Mountain, earthquakes associated with igneous activity would be related to basaltic intrusion and volcanism. Basaltic volcanism within 15-20 km of Yucca Mountain could produce earthquakes sufficient to produce ground motion at the repository. These effects have been include in the PSHA evaluations. Such earthquakes are incorporated in the PSHA as small magnitude background earthquakes.

Seismicity of volcanic rift zones worldwide indicates the mean maximum magnitude of dike-induced earthquakes is 3.8±0.8 and is generally less than 5 (Smith et al. 1998, Table 1). These types of earthquakes are generally small because the downdip extent of faults associated with dike fissuring is small (equal to or less than 5 km), resulting in small rupture areas (Smith et al. 1998, p. 155 and 158).

6.2.8 Igneous Activity (1.2.04.01.00)

FEP Description: Volcanism and magmatic activity could cause activation, creation and sealing of faults, changes in topography, changes in rock stress, deformation of rock, changes in groundwater temperatures, and severe perturbation to the integrity of the drifts.

Screening Decision: *Include* for eruptive and intrusive events, *Exclude* for indirect effects

Screening Decision Basis: *Include*: Meets Criteria / *Exclude*: Low Consequence for Indirect Effects

Screening Argument: Indirect effects of igneous activity (i.e., the effects of intrusions or extrusions that do not intersect the repository) are *Exclude* from the TSPA based on low consequence.

As discussed for FEPs 1.2.02.02.00, "Fractures" and 1.2.02.02.00, "Faults," activation and sealing of faults has been excluded due to low consequence. This is based on the analysis of the sensitivity of radionuclide transport to changes in fracture aperture for both the fault-zone scale, and at the mountain-wide scale (*Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 CRWMS M&O 2000b, Sections 6.2.2.2 and 6.2.2.3). Creation of faults or fractures was shown to be *Exclude* based on the low probability of formation of new faults in intact rock due to seismic stresses. It can be inferred from the supporting analysis that failure from an igneous event is more likely at preexisting fractures. Consequently, this aspect of the FEP is also *Exclude.*

Significant changes in topography by volcanic activity are *Exclude* due to low consequence. Surficial features associated with volcanoes found in the Yucca Mountain region are relatively small, and the construction of features like volcanic mountains or extensive lava fields would require igneous processes unlike those that are anticipated to be possible in the next 10,000 years in the Yucca Mountain region. The total eruptive volume of post-Miocene basalts is about 6 km^3, and all of the Quaternary-age centers of volcanism exhibit small volumes of approximately 0.14 km^3 or less (C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 CRWMS M&O 2000e, Section 6.2 and Table 4). The Quaternary-age features typically consist of a single main scoria cone surrounded by a small field of *aa* basalts (approximately 1 km extent) (C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 CRWMS M&O 2000e, Section 6.2). Small volcanic features may have local effects on infiltration due to changes in slope and soil characteristics. The large uncertainty in infiltration both under present conditions and due to future climate changes has been included explicitly in the TSPA, so additional changes from volcanic features would likely be within the range of uncertainty included in the TSPA. Changes in topography are therefore *Exclude*.

Changes in rock stress and rock deformation are discussed in FEP 1.2.04.02.00, "Igneous Activity Causes Changes to Rock Properties" and is *Exclude* based on low consequence. Changes in rock stress was the approach used in the analysis for *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b, Section 7) and was shown to have no consequence. The proximal cause of these effects for the analysis, however, was fault displacement rather than igneous activity. Igneous activity is likely to have a significant effect on rock stress and rock deformation in the immediate vicinity of the intruding dike or conduit. However, as described in FEP 1.2.04.02.00, "Igneous Activity Causes Changes to Rock Properties," the volume of rock that would be affected would be limited, compared to the repository area and the volume between the repository and the critical group located 20 km away. The small-volume volcanoes of the Yucca Mountain region and their associated features should produce very limited alteration of the hydrology based upon field-analogue data and the initial-stage numerical simulations performed by YMP scientists (Valentine et al. 1998, pp. 5-1 and 5-2). Consequently, change in rock stress and rock deformation is *Exclude* based on low consequence.

The effects of changes in groundwater temperature (as reflected by hydrothermally driven mass transfer) are discussed in FEP 1.2.10.02.00, and are *Exclude* based on low consequence. Again, the volume of material affected by an intrusion is minimal as reflected by the thickness of zones of alterations at natural-analogue sites (Valentine et al. 1999, pp. 5-1 and 5-2).

Severe perturbation to the integrity of the drifts could hypothetically occur with an igneous event. The perturbation could potentially include the damaging of waste packages. These types of effects are considered to be a direct (as opposed to indirect) consequence of an igneous event. Accordingly, they are *Include*. The treatment of these events is discussed in *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d). Additional discussion is provided in FEP 1.2.04.03.00, "Igneous Intrusion Into Repository."

TSPA Disposition: "Igneous Activity" as described in the FEP description is *Exclude* as discussed in the Screening Argument based on low consequence. However, direct effects of igneous events are *Include* for the TSPA as discussed in *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d).

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d)

Characterize Framework for Igneous Activity at Yucca Mountain, Nevada ANL-MGR-GS-000001 (CRWMS M&O 2000e)

Characterize Eruptive Processes at Yucca Mountain, Nevada ANL-MGR-GS-000002 (CRWMS M&O 2000g)

Dike Propagation Near Drifts ANL-WIS-MD-000015 (CRWMS M&O 2000h)

Analysis and Discussion: Igneous activity has occurred in the past in the Yucca Mountain region, and future occurrences of igneous activity in the region cannot be excluded. The TSPA includes explicit modeling of two types of igneous disruption of the disposal system. These include 1) direct releases of contaminated ash during volcanic eruptions, with contaminated ash resulting from conduits intersecting the repository and 2) the release of radionuclides into the groundwater from waste packages damaged by igneous intrusion. The modeling of these two igneous disruptions is described in detail in *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d).

For the eruptive (or extrusive) event scenario, the hypothetical eruption is assumed to occur through a section of the repository, entraining radionuclide-bearing wastes in the ash plume that disperses downwind and is deposited on the ground. For the eruptive event, a dike rises to the repository level and possibly intersects one or more drifts in the repository. At the repository level, zero to five vent conduits develop within the repository footprint and possibly intersect waste packages. The conduit erupts to the surface of the mountain entraining the waste in the ash. Inputs and parameters are specified in Section 6.1 of *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d). It is assumed for the referenced analysis that waste in waste packages and other components of the EBS that are damaged by igneous activity (either in the path of a conduit or because of proximity to an intrusive dike) are available to be entrained. It is also assumed for the referenced analysis that all intrusive events contain an eruptive phase and produce a conduit venting to the surface. Conduits within the repository footprint are assumed to be randomly located. Where conduits intersect drifts containing waste, all intersected waste packages are assumed available to be entrained in a pyroclastic eruption. Waste material is assumed to be fragmented, and is carried upward in the rising ash cloud. The mass of ash and entrained waste material included in each eruption is uncertain, and is treated as a variable in the analysis. The value of the variable is sampled from a distribution based on the volumes of ash erupted from analogous past volcanic eruptions. Once erupted, atmospheric transport of ash and radioactive material in the downwind direction is modeled using a software code that inputs characteristics of the igneous event and then calculates the ash and waste dispersal in the wind. The results of this model are then used to calculate dose to the critical group for the TSPA.

For the intrusive event, a hypothetical igneous dike intersects a section of the repository and partially or completely engulfs the intersected waste packages in magma. This waste is then available for transport in groundwater. The transport is dependent on the solubility limits of the waste and the availability of water. The movement of radionuclides released by the intrusive event is modeled directly in the TSPA using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d). It is assumed for the referenced analysis that waste packages and other components of the EBS that are damaged by proximity to an intrusive dike are completely destroyed, and all waste material from the destroyed components is available for transport in the unsaturated zone transport model. No credit is taken for encapsulation of waste and waste-package shells, which may slow or prevent water from reaching the waste.

As specified in DOE's Interim Guidance (Dyer 1999), consequences calculated for igneous disruption are weighted by the probability of the occurrence of the event (i.e., volcanic event intersecting the repository) before being combined with nominal performance to yield the expected annual dose. The basis for probability estimates and alternative estimates are discussed in C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.3.1.5 and 6.3.1.6). The discussion lists the mean value of the aggregate probability distribution as 1.5 x 10^{-8} intersection/year, with a 90 percent confidence interval of 5.4 x 10^{-10} to 4.9 x 10^{-8} intersections/year.

6.2.9 Igneous Activity Causes Changes to Rock Properties (1.2.04.02.00)

FEP Description: Igneous activity near the underground facility causes extreme changes to rock hydrologic and mineralogic properties. Permeabilities of dikes and sills and the heated regions immediately around them can differ from those of country rock. Mineral alterations can also change the chemical response of the host rock to contaminants.

Screening Decision: *Exclude*

Screening Decision Basis: Low Consequence

Screening Argument: This FEP is fully discussed in *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000b). "Igneous Activity Causes Changes to Rock Properties" is *Excluded* based on low consequence.

Sills and dikes initially intrude the country rock as molten material and then cool. Cooling joints are formed and resulting permeabilities may be greater, equivalent to, or less than the surrounding country rock. According to *Drift Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000h), future dikes should have a north to northeast direction, perpendicular to the least compressive stress and parallel or sub-parallel to the faults and fractures active in the present-day *in situ* stress field. Valentine et al. (1998, p. 5-32) indicate that the Paiute Ridge dike on the Nevada Test Site (NTS)

> . . . contains ubiquitous near-vertical joints that result in a pervasive platy texture with plates parallel to the dike-host contact. Conversely, with the exception of local cooling joints in fused wall rack (extending 10-20 cm into the wall rock, perpendicular to the dike margin) joints are never visible in the host rock along the length of the dike. The contact between the basalt and the tuff host rock is consistently smooth and shows nor brecciation.

This suggests that the primary direction of increased permeability is parallel with the dike margins, and is oriented roughly north to northeast. The anisotropic transmissivity observed in the Yucca Mountain region has a maximum principal transmissivity direction of approximately N30E, which is consistent with the fault and fracture orientation (Ferrill, Winterle, et al. 1999, p. 1). This parallel orientation of transmissivity coupled with the expected limited affected volume of the SZ and the generally low probability of an igneous intrusion indicates that dikes, even if differing in permeability, will not significantly affect groundwater flow patterns, and therefore changes in permeability are of little consequence with respect to repository performance. Changes in permeability are therefore *Exclude* based on low consequence.

Valentine et al. (1998, p 5-56) mention the possibility of perched water forming near low-permeability intrusive bodies, and the Secondary FEPs focus on the potential for a dike to provide a barrier to flow and/or impoundments. Because of the parallel orientation to saturated groundwater flow, a dike would not form a barrier or impoundment that would have any significant effect on flow in the SZ. In the unsaturated zone, the primary direction of groundwater flow is vertically through the fractures, although some horizontal flow component exists in the matrix. Because the joints on the dike margin are near-vertical, it would seem that the formation of a significant perched water zone is unlikely. Even if a perched water zone were to form and then were to drain, there would be only a minimal consequence as explained in Section 6.2.21 of this document.

It is also possible that the thermal and geochemical influence of igneous activity could affect the rock mineralogy surrounding the igneous intrusion. Igneous intrusions are generally confined to relatively thin zones of rock ranging from a few to a few hundred meters (Valentine et al. 1998, pp. 5-42 and 5-57). In particular, natural-analogue studies show that alteration is limited to less than 10 meters away from the contact at NTS natural-analogue sites (Valentine et al. 1998, pp. 5-41, 5-71 and 5-72). Valentine et al. (1999, p. 5-42) state that, "Based on natural-analogue sites, there is no indication for extensive hydrothermal circulation and alteration, brecciation and deformation related to magmatic intrusion, and vapor phase recrystallization during the magmatic intrusion into the vitric and zeolitized tuffs."

Because each component in the FEP description has been determined to be *Exclude* based on low consequence, this FEP is also *Exclude* based on low consequence. See also FEP 1.2.10.02.00, "Hydrologic Response to Igneous Activity" for additional discussions.

TSPA Disposition: The disposition of this FEP is fully addressed in the *YMP FEP Database* (1999b)

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *None*

Analysis and Discussion: See TSPA Disposition

6.2.10 Igneous Intrusion Into Repository (1.2.04.03.00)

FEP Description: Magma from an igneous intrusion flows into the drifts and extends over a large portion of the repository site, forming a sill. The sill could be limited to the drifts or a continuous sill could form along the plane of the repository, bridging between adjacent drifts.

Screening Decision: *Include* (as a dike rather than as a sill)

Screening Decision Basis: Meets Criteria

Screening Argument: Igneous Intrusion Into Repository is included as described under the TSPA Disposition.

TSPA Disposition: Consequences of an igneous intrusion into the repository are explicitly included in the TSPA-SR and appropriately weighted by the probability of the occurrence of the event. The type of intrusion, however, is chosen to be a dike (a vertical tabular body) rather than a sill (a horizontal tabular body). This redefinition is based on the results of *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000h, Section 6.3) In general, the direction of dike propagation will be perpendicular to the lines of least principle stress, which are typically horizontal or sub horizontal in the Yucca Mountain region, and hence dike formation is preferable to sill formation. Under current and post-thermal repository conditions, this will result in dikes oriented roughly N30E (or north to northeast). During the thermal period (duration of approximately 2,000 years), horizontal deflection of dikes below the repository level could occur because the least principal stress will be vertical (*Dike Propagation Near Drifts* ANL-WIS-MD-000015 CRWMS M&O 2000h, Figures 2 and 3).

The primary concern will be associated with either a magmatic intrusion directly into the repository, or a possible eruption of volcanic ash containing waste particles. The TSPA includes explicit modeling of these two types aspects of igneous disruption of the disposal system, and they are appropriately weighted by the probability of their occurrence. The consequence modeling is performed in *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d). For both the groundwater release and ashfall releases, dose to the critical group are calculated in the TSPA.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d)

Characterize Framework for Igneous Activity at Yucca Mountain, Nevada ANL-MGR-GS-000001 (CRWMS M&O 2000e)

Characterize Eruptive Processes at Yucca Mountain, Nevada ANL-MGR-GS-000002 (CRWMS M&O 2000g)

Dike Propagation Near Drifts ANL-WIS-MD-000015 (CRWMS M&O 2000h)

Analysis and Discussion: The TSPA includes explicit modeling of the consequences of igneous disruption of the disposal system.

For the intrusive event, an igneous dike intersects a section of the repository and partially or completely engulfs the intersected waste packages in magma. This waste is then available for transport in groundwater. The intrusive event is modeled directly in the TSPA using existing flow-and-transport models developed for analysis of the nominal performance scenario. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d). The referenced analysis assumes that waste packages and other components of the EBS that are damaged by proximity to an intrusive dike are completely destroyed, and all waste material is available for transport in the unsaturated zone transport model. The transport is dependent on the solubility limits of the waste and the availability of water. No credit is taken for encapsulation of waste and waste-package shells, which may slow or prevent water from reaching the waste.

As specified in DOE's Interim Guidance (Dyer 1999), consequences calculated for igneous disruption are weighted by the probability of the occurrence of the event (i.e., volcanic event intersecting the repository) before being combined with nominal performance to yield the expected annual dose. The basis for probability estimates and alternative estimates is discussed in *Characterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.3.1.5 and 6.3.1.6). The discussion lists the mean value of the aggregate probability distribution as 1.5×10^{-8} intersection/year, with a 90 percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8} intersections/year.

6.2.11 Magma Interacts with Waste (1.2.04.04.00)

FEP Description: An igneous intrusion in the form of a dike occurs through the repository, intersecting waste. This leads to accelerated waste container failure (e.g., attack by magmatic volatiles, damage by fragmented magma, thermal effects) and dissolution of waste (Commercial Spent Nuclear Fuel (CSNF), Defense Spent Nuclear Fuel (DSNF), and DOE High Level Waste (DHLW)

Screening Decision: *Include*

Screening Decision Basis: Meets Criteria

Screening Argument: Magma Interacts with Waste is *Include* as described under the TSPA Disposition.

TSPA Disposition: The primary focus of this FEP is magmatic intrusion directly into the repository. Interactions between the intrusion, the waste, and the waste packages are included in the TSPA through conservative assumptions, as described in *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d, Section 5).

For the intrusive event, the analysis assumes that an igneous dike intersects a section of the repository and partially or completely engulfs the intersected waste packages in magma. The consequences of the intrusive event is modeled directly in the TSPA using existing flow-and-transport models developed for analysis of the nominal performance scenario. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d). It is assumed for the referenced analysis that waste packages and other components of the EBS that are damaged by proximity of an intrusive dike are completely destroyed, and that all waste material in damaged waste packages would be available for transport as described in the UZ transport model. The transport is dependent on the solubility limits of the waste and the availability of water. No credit is taken for encapsulation of waste and waste-package shells in the cooled magma, which could slow or prevent water from reaching the waste. Doses to the critical group from this event are calculated in the TSPA.

The volume of waste available for transport is directly dependent on the characteristics of the intrusion (size of conduit, number of conduits, and location). These variables are addressed in C*haracterize Framework for Eruptive Processes at Yucca Mountain*, *Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000g, Section 6.5).

Eruptive processes are addressed in FEP 1.2.04.06.00, "Basaltic Cinder Cone Erupts Through the Repository".

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d)

C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e)

Dike Propagation Near Drifts ANL-WIS-MD-000015 (CRWMS M&O 2000h)

Analysis and Discussion: In the TSPA analysis, all waste packages that are affected by intrusion are assumed to be damaged sufficiently that they provide no further protection for the waste. Fuel-rod cladding within these packages is also assumed to be sufficiently damaged to provide no further protection, and the waste material is available for dissolution and transport by groundwater. All waste types are included in the analysis in the same way that they are included in the TSPA analyses of nominal performance. Commercial spent nuclear fuel is treated as one waste type, and the inventory of all other waste types is aggregated into a second type. No credit is taken for encapsulation of waste and waste-package shells in the cooled magma, which may slow or prevent water from reaching the waste. The transport of the waste is dependent on the solubility limits of the waste and the availability of water. Doses to the critical group from this event are calculated in the TSPA.

These assumptions do not explicitly consider the uncertainties associated with the effects of attack by magmatic volatiles, dissolution of waste in the basaltic melt, or mechanical damage due to dynamic interactions with moving magma. The assumption of complete failure of affected packages is based on thermal calculations that indicate that deformation of the welds between the package shell and the lid at the end of the package may cause waste packages to fail from internal stresses at 1200 degrees C (Calculation, *Waste Package Behavior in Magma,* CAL-EBS-ME-000002 CRWMS M&O 1999g). This type of failure would not remove waste from the package shell, and it is conservative to assume the damaged packages provide no additional protection. Attack by magmatic volatiles and mechanical deformation could further damage the packages, but would not result in conditions more extreme than the total removal of the package assumed for this analysis.

Dissolution of waste in basaltic melt is not considered explicitly, but is conservatively bounded by assuming that waste is exposed directly to groundwater without any protection from the surrounding basalt. Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Any waste dissolved in the basaltic melt (or simply entrained within it as a solid) would be less exposed to groundwater than is assumed by the approach taken in these assumptions.

As specified in DOE's Interim Guidance (Dyer 1999), consequences calculated for igneous disruption are weighted by the probability of the occurrence of the event (i.e., volcanic event intersecting the repository) before being combined with nominal performance to yield the expected annual dose. The basis for probability estimates and alternative estimates are discussed in C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.3.1.5 and 6.3.1.6). The discussion lists the mean value of the aggregate probability distribution as 1.5×10^{-8} intersection/year, with a 90 percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8} intersections/year.

6.2.12 Magmatic Transport of Waste (1.2.04.05.00)

FEP Description:	An igneous intrusion occurs through the repository, intersecting waste. Some of the waste (entrained, dissolved, or volatilized) is then transported away from the repository. Of most concern is transport directly to the land surface.
Screening Decision:	*Exclude* for transport in liquid magma / *Include* for pyroclastic transport

Screening Decision Basis: *Exclude*: Low Consequence / *Include*: Meets Criteria

Screening Argument: The critical group is specified by guidance to be located 20 km from the repository. The total eruptive volume of the post-Miocene basalts is about 6 km^3, and all of the Quaternary-age centers of volcanism exhibit small volumes of approximately 0.14 km^3 or less (C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.2 and Table 4). The Quaternary-age features typically consist of a single main scoria cone surrounded by a small field of *aa* basalts (approximately 1 km extent) (C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.2). Consequently, it is very unlikely that extruded basalts with entrained wastes will reach the critical group. For the same reasons a pyroclastic flow (as opposed to a pyroclastic eruption or ashfall) is also excluded. Magmatic transport in liquid magma is therefore *Exclude* based on low consequence.

The transport of waste in molten magma will have less effect on radiation exposure to the critical group 20 kilometers from the site than will the conservative assumption that the affected waste is fully exposed to seeping groundwater and available for transport. Transportation of any volatilized radionuclides over the distances for which temperatures will remain high enough will have no additional effect. Volatilized and redeposited radionuclides will not be any more accessible to groundwater transport than in the exposed state assumed for the solid waste material. Consequently, transport of waste in liquid magma is *Exclude* based on low consequence.

Other types of magmatic transport (e.g., in lava flowing within the drift, in lava reaching the land surface directly above the vent, or released to the atmosphere as a gaseous phase following vaporization by magmatic heat) are not included explicitly in the TSPA model. The conservative assumption that all waste packages affected by the intrusion fail, and that waste is exposed directly to groundwater in the drifts, effectively bounds the consequences of radionuclide transport mechanisms. Therefore, Magmatic Transport of Waste is *Exclude* based on low consequence.

TSPA Disposition: Magmatic Transport of Waste is *Exclude* as discussed in the Screening Argument. Transport via an eruptive event and through pyroclastic eruption is *Include* and is addressed in FEPs 1.2.04.07.00, "Ashfall" and 1.2.04.06.00, "Basaltic cinder cone erupts through the repository." Magma interaction with waste is *Include* as described for FEP 1.2.04.04.00.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d)

Characterize Framework for Igneous Activity at Yucca Mountain, Nevada ANL-MGR-GS-000001 (CRWMS M&O 2000e)

Characterize Eruptive Processes at Yucca Mountain, Nevada ANL-MGR-GS-000002 (CRWMS M&O 2000g)

Dike Propagation Near Drifts ANL-WIS-MD-000015 (CRWMS M&O 2000h)

Analysis and Discussion: As specified in DOE's Interim Guidance (Dyer 1999), consequences calculated for igneous disruption are weighted by the probability of the occurrence of the event (i.e., volcanic event intersecting the repository) before being combined with nominal performance to yield the expected annual dose. The basis for probability estimates and alternative estimates are discussed in C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.3.1.5 and 6.3.1.6). The discussion lists the mean value of the aggregate probability distribution as 1.5×10^{-8} intersection/year, with a 90 percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8} intersections/year.

6.2.13 Basaltic Cinder Cone Erupts Through the Repository (1.2.04.06.00)

FEP Description: As a result of an igneous intrusion, a cinder cone forms at land surface. The conduit(s) supplying the vent(s) of the cone pass(es) through the repository, interacting with and entraining waste.

Screening Decision: *Include*

Screening Decision Basis: Meets Criteria

Screening Argument: Basaltic Cinder Cone Erupts Through the Repository is included as described in the TSPA Disposition.

TSPA Disposition: Consequences of an igneous intrusion into the repository are explicitly included in the TSPA-SR, appropriately weighted by the probability of occurrence of the event. The TSPA includes explicit modeling of two types of igneous disruptions of the disposal system. These include 1) direct releases of contaminated ash during volcanic eruptions, with contaminated ash resulting from conduits intersecting the repository and 2) the release of radionuclides into the groundwater from waste packages damaged by igneous intrusion. The modeling of these two igneous disruptions is described in detail in *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d). This FEP "Basaltic Cinder Cone Erupts through the Repository" in *Include* and is addressed through the modeling of the eruptive event.

The distributions used for modeling dike characteristics and for the number of eruptive cones and centers is presented in C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.5.3.1). Of particular note, the conditional distribution for the number of eruptive centers inherently addresses the consequences of Secondary FEPs 1.2.04.06.01 Vent Jump." Properties of the basaltic eruption are described in *Characterize Eruptive Processes at Yucca Mountain*, *Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000g) and are based on the observed characteristics of past basaltic eruptions in the Yucca Mountain region and other analogous eruptions. This characterization includes consideration of the vent conduit diameters and thereby addresses the consequence of the Secondary FEP 1.2.04.06.02 "Vent erosion".

For the eruptive (or extrusive) event, the eruption occurs through a section of the repository entraining radionuclide bearing wastes in the ash plume that is then dispersed downwind and deposited on the ground. For the eruptive event, a dike rises to the repository level and intersects one or more drifts in the repository. At the repository level, from zero to five conduits develop within the repository footprint, and possibly intersect waste packages. It is conservatively assumed that all the material in damaged waste packages is available to be entrained in the rising pyroclastic eruption. The ash cloud rises through the conduit and erupts (with the entrained waste) at the surface of the mountain.

Inputs and parameters are specified in Section 6.1 of *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d). It is assumed for the referenced analyses that waste packages and other components of the EBS that are damaged by igneous activity (either in the path of a conduit or because of proximity to an intrusive dike) are completely destroyed. It is also assumed that all intrusive events contain an eruptive phase and produce a conduit venting to the surface. Conduits within the repository footprint are assumed to be randomly located. Where conduits intersect drifts containing waste, the contents of all intersected waste packages are assumed available to be entrained in a pyroclastic eruption. Waste material is assumed to be fragmented, and is carried upward in the rising ash cloud. The mass of ash and entrained waste material included in each eruption is uncertain, and is treated as a variable in the analysis. The value of the variable is sampled from a distribution based on the volumes of ash erupted from analogous past volcanic eruptions. Once erupted, atmospheric transport of ash and radioactive material in the downwind direction is modeled using a software code that inputs characteristics of the igneous event and then calculates the ash and waste dispersal in the wind. The results of this model are then used to calculate dose to the critical group for the TSPA.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d)

Characterize Eruptive Processes at Yucca Mountain, *Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000g)

C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e)

Characterize Eruptive Processes at Yucca Mountain, Nevada ANL-MGR-GS-000002 (CRWMS M&O 2000g)

Dike Propagation Near Drifts ANL-WIS-MD-000015 (CRWMS M&O 2000h)

Analysis and Discussion: As specified in DOE's Interim Guidance (Dyer 1999), consequences calculated for igneous disruption are weighted by the probability of the occurrence of the event (i.e., volcanic event intersecting the repository) before being combined with nominal performance to yield the expected annual dose. The basis for probability estimates and alternative estimates are discussed in C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.3.1.5 and 6.3.1.6). The discussion lists the mean value of the aggregate probability distribution as 1.5×10^{-8} intersection/year, with a 90 percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8} intersections/year.

6.2.14 Ashfall (1.2.04.07.00)

FEP Description: Finely-divided waste particles are carried up a volcanic vent and deposited at land surface from an ash cloud or pyroclastic flow.

Screening Decision: *Include*: ash cloud and surface deposition / *Exclude*: pyroclastic flow.

Screening Decision Basis: Meets Criteria

Screening Argument: Ashfall is included in the TSPA as described under the TSPA Disposition.

TSPA Disposition: Intersection of waste packages in the repository by a conduit feeding a volcanic eruption at land surface is explicitly included in the TSPA model for the Igneous Activity Disruptive Scenario, as described in *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d, Section 6.1).

For the eruptive (or extrusive) event, the hypothetical eruption occurs through a section of the repository entraining radionuclide bearing wastes in the ash plume that is then dispersed downwind and deposited on the ground. For the eruptive event assumed for the TSPA, a dike rises to the repository level and intersects one or more drifts in the repository. At the repository level, zero to five vent conduits develop within the repository footprint, possibly intersecting waste packages. The conduit erupts to the surface of the mountain entraining the waste in the ash. The analysis conservatively assumes that all erupted volume is ash. Inputs and parameters are specified in Section 6.1 of *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d).

Inputs and parameters are specified in Section 6.1 of *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS

M&O 2000d). It is assumed for the referenced analyses that waste packages and other components of the EBS that are damaged by igneous activity (either in the path of a conduit or because of proximity to an intrusive dike) are completely destroyed. It is also assumed that all intrusive events contain an eruptive phase and produce a conduit venting to the surface. Conduits within the repository footprint are assumed to be randomly located. Where conduits intersect drifts containing waste, it is conservatively assumed that the entire waste content of all intersected waste packages are available to be entrained in the eruption. Waste material is assumed to be fragmented, and is carried upward in the rising pyroclastic/ash cloud. The mass of ash and entrained waste material included in each eruption is uncertain, and is treated as a variable in the analysis. The value of the variable is sampled from a distribution based on the volumes of ash erupted from analogous past volcanic eruptions. Once erupted, atmospheric transport of ash and radioactive material in the downwind direction is modeled using a software code that inputs characteristics of the igneous event and then calculates the ash and waste dispersal in the wind. The results of this model are then used to calculate dose to the critical group for the TSPA.

Pyroclastic flows (contrasted to ashflows or pyroclastic eruptions) are *Exclude* due to the distance of the critical group specified by guidance as located 20 km from the repository. The total eruptive volume of post-Miocene basalts is about 6 km^3, and all of the Quaternary-age centers of volcanism exhibit small volumes of approximately 0.14 km^3 or less (C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.2 and Table 4).

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation* ANL-WIS-MD-000017 (CRWMS M&O 2000d)

Characterize Eruptive Processes at Yucca Mountain, *Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000g)

C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e)

Dike Propagation Near Drifts ANL-WIS-MD-000015 (CRWMS M&O 2000h)

Analysis and Discussion: The TSPA model estimates radionuclide concentrations in contaminated ash falling at the location of the critical group 20 km south of the repository. Properties of the basaltic eruption are described in *Characterize Eruptive Processes at Yucca Mountain*, *Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000g), and are based on the observed characteristics of past basaltic eruptions in the Yucca Mountain region and other analogous eruptions.

Uncertainty in the specific parameters characterizing an eruptive event, including the final diameter of the conduit, the volume of material erupted, the energy of the eruption, and the size of the ash particles, is included in the TSPA through sampling from cumulative distribution functions based on available information. (See *Igneous Consequence Modeling for the Total System Performance Assessment-Site Recommendation Analysis* ANL-WIS-MD-000017: CRWMS M&O 2000d, Section 6.1)

As specified in DOE's Interim Guidance (Dyer 1999), consequences calculated for igneous disruption are weighted by the probability of the occurrence of the event (i.e., volcanic event intersecting the repository) before being combined with nominal performance to yield the expected annual dose. The basis for probability estimates and alternative estimates are discussed in C*haracterize Framework for Igneous Activity at Yucca Mountain*, *Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000e, Section 6.3.1.5 and 6.3.1.6). The discussion lists the mean value of the aggregate probability distribution as 1.5×10^{-8} intersection/year, with a 90 percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8} intersections/year.

6.2.15 Hydrologic Response to Seismic Activity (1.2.10.01.00)

FEP Description: Seismic activity, associated with fault movement, may create new or enhanced flow pathways and/or connections between stratigraphic units, or it may change the stress (and therefore fluid pressure) within the rock. These responses have the potential to significantly change the surface- and groundwater- flow directions, water level, water chemistry, and temperature.

Screening Decision: *Exclude*

Screening Decision Basis: Low Consequence

Screening Argument: This FEP includes the effects of seismic activity on unsaturated- and saturated-zone flow and transport at the mountain scale and for drift seepage. It also includes the possibility of a water table rise in response to seismic activity (e.g., seismic pumping).

Seismic activity (regardless of origin) in the UZ would either be transient in nature, or result in changes to fracture hydrologic characteristics, as expressed through the parameter of fracture aperture. The effects of changes to the fracture system due to geologic effects on mountain-scale flow and radionuclide transport have been investigated using a sensitivity approach *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b). The effects of changes in fracture apertures were examined because several fracture properties (permeability, capillary pressure, and porosity) are functions of fracture aperture. The results indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture. Therefore, seismic effects on the unsaturated zone are *Exclude* based on low consequence.

Earthquakes effect changes in groundwater levels, often at distances far removed from the epicenter. Such changes are usually transient, although the reversion to pre-earthquake levels may occur over several months. Muir-Wood and King (1993, pp. 22054, 22059, and 22060) assert that the most significant changes, primarily measured in terms of stream discharges) are related to normal-fault earthquakes, while Gauthier et al. (1996, p. 164) indicate that for Yucca Mountain, the greatest strain-induced changes in water-table elevation occur with strike-slip faults.

Gauthier et al. (1996, p. 163-164) have analyzed the potential effects of seismic activity on contaminant transport in the SZ due to changes in water-table elevation. Their simulations of the timing, magnitude, and duration of water-table rise indicate a maximum rise of 50 meters within an hour of the simulated seismic event. The simulated system returns to steady-state conditions within 6 months. Gauthier et al. (1996, pp. 163-164) concluded that:

> In general, seismically induced water-table excursions caused by poroelastic coupling would not influence the models presently being used to determine long-term performance of a repository at Yucca Mountain; therefore, we excluded them from the total-system simulations.

Alternative perspectives on seismic pumping and water-level changes are discussed in the draft Environmental Impact Statement (DOE 1999, p 3-49)

TSPA Disposition: Hydrologic Response to Seismic Activity is *Exclude* as described under the Screening Argument.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: None

Analysis and Discussion: See Screening Argument

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6.2.16 Hydrologic Response to Igneous Activity (1.2.10.02.00)

FEP Description: Igneous activity may change the groundwater flow directions, water level, water chemistry, and temperature. Igneous activity includes magmatic intrusions, which may change rock properties and flow pathways, and thermal effects, which may heat up groundwater and rock.

Screening Decision: *Exclude*

Screening Decision Basis: Low Consequence

Screening Argument: Valentine et al. (1998, p. 5-56) indicate that the long term effects of magmatic intrusions could include the possibility of perched water near low permeability intrusive bodies, possible fast paths along intrusion-induced fractures, and reduced chemical retardation properties of the country rock resulting from hydrothermal alteration.

According to *Drift Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000h), future dikes should have a north to northeast direction, perpendicular to the least compressive stress and parallel or sub-parallel to the faults and fractures active in the present-day *in situ* stress field. Valentine et al. (1998, p. 5-32) indicate that the Paiute Ridge dike on the Nevada Test Site (NTS)

> . . . contains ubiquitous near-vertical joints that result in a pervasive platy texture with plates parallel to the dike-host contact. Conversely, with the exception of local cooling joints in fused wall rack (extending 10-20 cm into the wall rock, perpendicular to the dike margin) joints are never visible in the host rock along the length of the dike. The contact between the basalt and the tuff host rock is consistently smooth and shows no brecciation.

This suggests that the primary direction of increased permeability is parallel with the dike margins, and will be oriented roughly north to northeast. The anisotropic transmissivity observed in the Yucca Mountain region has a maximum principal transmissivity direction of approximately N30E, which is consistent with the fault and fracture orientation (Ferrill, Winterle et al. 1999, p. 1). This parallel orientation coupled with the expected limited affected volume of the SZ and the generally low probability of an igneous intrusion indicates that dikes, even if differing in permeability from the host rock, will not significantly affect groundwater flow patterns. Therefore, changes in permeability and flow directions due to igneous activity are of minimal consequence with respect to repository performance.

Valentine et al. (1998, p 5-56) mention the possibility of perched water forming near low-permeability intrusive bodies, and the Secondary FEPs focus on the potential for a dike to provide a barrier to flow and/or impoundments. Because of the parallel orientation to saturated ground water flow, it is unlikely that a dike would form a barrier or impoundment in the SZ. Furthermore, the TSPA-VA evaluation for disruptive events (CRWMS M&O 1998f, Section 10.5.3) suggests that intrusion of a dike would have negligible impact on repository performance due to changes in flow in the saturated zone. Changes in permeability and flow systems are therefore *Exclude* based on low consequence.

Based on the study of natural-analogue sites, Valentine et al. (1999, p. 5-2) state that chemical and mineralogical studies of host tuffs indicated that for shallow, small volume basaltic intrusions, alteration is limited to within a few tens of meters of the intrusion itself. More particularly, from a study of the Paiute Ridge analogue site, there is no indication for extensive hydrothermal circulation and alteration, brecciation and deformation related to magmatic intrusion, and vapor phase recrystallization during the magmatic intrusions into the vitric and zeolited tuffs. (Valentine et al. 1999 p. 5-42). The analogue studies show that alteration is quite limited, typically only found within 5-10 meters of intrusions (Valentine et al. 1999, p. 5-41). At the Paiute Ridge site, low temperature, secondary minerals persist near the contact with intrusions (Valentine et al. 1998, p. 5-46). This suggests that little destruction of sorptive minerals is expected. Given the limited area of alteration around the intrusion, the affect of alteration is assumed to be of negligible consequence to repository performance and is therefore *Exclude.*

Valentine et al. (1999, p 5-86) also have considered the effects of hydrothermal systems resulting from igneous intrusions. Findings from the Paiute Ridge analogue site indicated that " the occurrence of clinoptilolite and opal also suggests that thermal transfer into the adjacent country rock was minimal" (Valentine et al. 1999, p. 5-57). Findings from the Grants Ridge site suggests the absence of a hydrothermal system except for localized recrystallization of volcanic glass within the contact zone (Valentine et al. 1999, p. 5-74). Further, they concluded that ". . . an intrusion at Yucca Mountain would not result in large amounts of hydrothermally driven mass transfer" (Valentine et al. 1998, p. 5-74). Consequently, the development of hydrothermal systems from igneous activity is *Exclude* based on low consequence due to their limited size respective to the repository footprint.

Based on their initial stage work with highly simplified systems used to represented Yucca Mountain, Valentine et al. (1999 p. 5-86) suggest that the horizontal distance over which an intrusion affects convective air flow is always less than 2.5 km, and that the dike or sill particles representing magmatic volatiles never travel more that approximately 500 m horizontally.

The potential for change in rock properties due to igneous activity is discussed in FEP 1.2.04.02.00 and is *Exclude* based on low consequence.

The Hydrologic Response to Igneous Activity is therefore *Exclude* based on low consequence.

TSPA Disposition: Hydrologic Response to Igneous Activity is *Exclude* as described in the Screening Argument

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: None

Analysis and Discussion: Another concern is the possibility that a large steam explosion could occur, such that a large phreatic or a phreatomagmatic crater (maar) forms. Such a process could directly excavate waste and disperse it over a large area of the surrounding surface. For a large, disruptive steam explosion to occur, magma must come in rapid contact with a large volume of water at a shallow depth. Confining pressures must be sufficiently low to permit the formation of steam (gas-phase water), and as the steam violently expands, to allow disruption of the surrounding rock. These mechanisms were considered by Crowe, Wohletz et al. (1986, p. 58-59). Although rising magma at Yucca Mountain would contact water in the saturated zone, Crowe, Wohletz et al. concluded that "exhumation of a repository by explosive cratering associated with water/magma interaction is unlikely – the depth of burial of a repository at Yucca Mountain exceeds the crater depth of the largest known hydrovolcanic craters."

6.2.17 Rockfall (Large Block) (2.1.07.01.00)

FEP Description: Rockfalls occur large enough to mechanically tear or rupture waste packages

Screening Decision: *Exclude*

Screening Decision Basis: Low Consequence

Screening Argument: "Rockfall (large block)" is *Exclude* from the TSPA based on low consequence.

An analysis of the possible formation of key blocks within the repository horizon has been provided by the *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a). Block failure due to seismic and thermal effects has also been analyzed. Analysis activities involved using analytical methods, including the Universal Distinct Element Code (UDEC) and the DRKBA numerical code and performing calculations and statistical analyses to determine the expected quantities, locations, size distributions and frequencies of rockfall, for the repository emplacement drifts. The results indicate that seismic, time-dependent, and thermal effects have a relatively minor influence on rockfall probabilities.

Additionally, the LADS for the repository is Enhanced Design Alternative II (CRWMS M&O 1999d, pp. 4-16 and 4-17), which includes a drip shield and backfill as barriers. The presence of these design features precludes rockfall as a credible occurence contributing to waste-package failure.

Because the base-case rockfall scenario shows minimal rockfall, thermal and seismic impacts on rockfall are expected to be minimal, and the design elements include a drip shield and backfill that will minimize any rockfall that will occur, there is no likely mechanism for creating significant damage to the waste package. Because of the expected negligible waste-package damage, there is no mechanism that would result in a release of radionuclides from the waste package, and calculated dose estimates can not therefore be significantly changed. Consequently, rockfall is *Exclude* from the TSPA based on low consequence. The secondary FEPs (see CRWMS M&O 1999b), which includes the impact of rockbursts (a sudden rock-mass failure) onto waste packages (FEP No. 2.1.07.01.01), are also *Exclude* for these reasons.

TSPA Disposition: Rockfall (large block) is *Exclude* from TSPA as described under the Screening Argument.

IRSR-Issues: Repository Design and Thermal-Mechanical Effects:
to be updated for REV 01

Related AP-3.10Q: *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a)

Analysis and Discussion: Key blocks are blocks formed in the rock mass surrounding an excavation (by the intersection of three or more planes of structural discontinuity) that are removable and oriented in an unsafe manner so that they are likely to move into the opening unless restraint is provided. An analysis of the possible formation of key blocks within the repository horizon has been provided in the *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a). The key-block analysis has examined unsupported drifts, both with and without backfill, and applied static-, thermal-, and seismic-loading conditions.

This analysis involved using analytical methods, including the UDEC and the DRKBA numerical codes, and performing calculations and statistical analyses to determine the expected quantities, locations, size distributions, and frequencies of rockfall, for the repository emplacement drifts. Input data for both the UDEC and DRKBA analyses included fracture-geometry data from ESF tunnel mapping, and rock density, joint-strength properties, and intact-rock elastic properties from laboratory testing. The key design-related parameters (drift diameter and orientation) are discussed in *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a, p. 12). Peak ground accelerations at the repository horizon were also used in the assessment of seismic effects on block size. The peak ground accelerations analyzed included 0.14 g, 0.30 g, and 0.43 g, which correspond to the 10^{-3}, 2×10^{-4}, and 10^{-5} annual exceedance probabilities.

Due to the limitation of DRKBA, seismic load simulations can not be performed directly for the drift openings. An alternative method with a reduction of joint-strength parameters was used to account for the seismic effect. The reduced joint-strength parameters, cohesion, and friction angle are provided in *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a, p. 32). This method was verified based on test runs using UDEC. In the assessment of thermal and time-dependent effects on rockfall in the drift-degradation analysis, joint cohesion has been conservatively reduced from a laboratory test value of 0.86 MPa to a value of 0.01 MPa after 10,000 years (*Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00: CRWMS M&O 2000a, p. 63).

The LADS Report (CRWMS M&O 1999d, Fig. 5-1) for the repository includes emplacements drifts located in three lithologic units, including the Topopah Spring Tuff, crystal-poor member, middle nonlithophysal (Tptpmn), the Topopah Spring Tuff, crystal-poor member, lower lithophysal (Tptpll), and the Topopah Spring Tuff, crystal-poor member, lower nonlithophysal (Tptpln).

Block sizes for each of these units have been evaluated. The predicted numbers of key blocks per unit length of drift are generally low, with a maximum of 40 blocks per kilometer in the Tptpmn lithologic unit (*Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00: CRWMS M&O 2000a, p. 51). For the Tptpmn unit, 90 percent of the blocks were less than 1.7 cubic meters. The number of key blocks predicted for Tptpll unit is minimal (3 blocks per kilometer). The emplacement-drift openings are predominantly located in the Tptll and were not affected by rockfall. For the Tptpll, 90 percent of the blocks were less than 0.2 cubic meters. For the Tptpln unit, 90 percent of the blocks were less than 10.2 cubic meters

The seismic effects on rockfall were compared to the static key-block results. The comparison shows that there is an insignificant impact on the number of rockfalls for the 10^{-3} annual exceedance probability (peak ground acceleration of 0.14 g), and only a minor impact for both the mean 2 x 10^{-4} and mean 10^{-5} annual exceedance probabilities.

Because backfill is part of the EBS during the post-closure period, backfill was included in the drift-degradation analysis for the consideration of time-dependent and thermal effects. It is apparent that the blocks that form around the tunnel springline (see glossary – Attachment I) will no longer occur in the analysis with backfill. Only minor increases in the number of key blocks are predicted between year 200 and year 2,000. No change is predicted from year 2,000 to year 10,000.

The LADS design for the repository is Enhanced Design Alternative II (CRWMS M&O 1999d, pp. 4-16 and 4-17), which includes a drip shield and backfill. The presence of these design features precludes rockfall as a credible scenario contributing to waste-package failure, and the FEP is *Exclude* based on low consequence. The secondary FEP, which includes the impact of rockbursts on waste packages (FEP No. 2.1.07.01.01, see *YMP FEP Database*), is also *Exclude* for these reasons.

6.2.18 Mechanical Degradation or Collapse of Drift (2.1.07.02.00)

FEP Description: Partial or complete collapse of the drifts, as opposed to discrete rockfall, could occur as a result of seismic activity, thermal effects, stresses related to excavation, or possibly other mechanisms. Drift collapse could affect stability of the engineered barriers and waste packages. Drift collapse may be localized as stoping at faults or other geologic features. Rockfalls of small blocks may produce rubble throughout part or all of the drifts.

Screening Decision: *Exclude*

Screening Decision Basis: Low Consequence

Screening Argument: Mechanical degradation or collapse of drift is *Exclude* from the TSPA based on low consequence.

It is unlikely that drift degradation could cause penetration of the designed engineered barriers and adversely impact a waste package. The LADS for the repository is Enhanced Design Alternative II (CRWMS M&O 1999d, p. 4-16 and 4-17), which in addition to the waste package itself, includes a drip shield and backfill as barriers. The presence of these design features precludes drift degradation as a credible scenario contributing to waste-package failure. If no damage to the waste package occurs, there is no mechanism for increasing a radionuclide release, and no mechanism for increasing the calculated doses. Consequently, this FEP is *Exclude* based on low consequence.

TSPA Disposition: Mechanical degradation or collapse of drift is *Exclude* from TSPA as described under the Screening Argument

IRSR-Issues: Repository Design and Thermal-Mechanical Effects:

to be updated for REV 01

Related AP-3.10Q: *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a)

Analysis and Discussion: The main failure mechanism contributing to drift degradation or collapse is rock blocks falling into the drift. Key blocks are blocks formed in the rock mass surrounding an excavation (by the intersection of three or more planes of structural discontinuity) that are removable and oriented in an unsafe manner so that they are likely to move into the opening unless restraint is provided. An analysis of the possible formation of key blocks within the repository horizon has been provided in the *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a). The key-block analysis has examined unsupported drifts, both with and without backfill, and applied static-, thermal-, and seismic-loading conditions.

Analyses involved using analytical methods, including the UDEC and the DRKBA numerical code, to perform calculations and statistical analyses to determine the expected quantities, locations, size distributions, and frequencies of rockfall, for the repository emplacement drifts.

Input data for both the UDEC and DRKBA analyses included fracture geometry data from ESF tunnel mapping, and rock density, joint-strength properties, and intact-rock elastic properties from laboratory testing. The key design-related parameters (drift diameter and orientation) are discussed in *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a, p. 12). Peak ground accelerations at the repository horizon were also used in the assessment of seismic effects on block size. The peak ground accelerations analyzed included 0.14 g, 0.30 g, and 0.43 g, which correspond to the 10^{-3}, 2×10^{-4}, and 10^{-5} annual exceedance probability values.

Due to the limitation of DRKBA, simulation of seismic loads can not be performed directly for drift openings. An alternative method with a reduction of joint-strength parameters was used to account for the seismic effects. The reduced joint-strength parameters, cohesion and friction angle, are provided in *Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00 (CRWMS M&O 2000a, p. 32). This method was verified based on test simulations using UDEC. In the assessment of thermal and time-dependent effects on rockfall in the drift-degradation analysis, joint cohesion has been conservatively reduced from a laboratory test value of 0.86 MPa to a value of 0.01 MPa after 10,000 years (*Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00: CRWMS M&O 2000a, p. 63).

The LADS Report (CRWMS M&O 1999d, Fig. 5-1) for the repository includes emplacements drifts located in three lithologic units, including the Tptpmn, Tptpll, and Tptpln. The predicted numbers of key blocks per unit length of drift are generally low, with a maximum of 40 blocks per kilometer in the Tptpmn lithologic unit (*Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00: CRWMS M&O 2000a, p. 51). The highest percentage of drift affected by rockfall was 16% in the Tptpmn unit (*Drift Degradation Analysis* ANL-EBS-MD-000027 REV 00: CRWMS M&O 2000a, p. 63). The emplacement-drift openings are predominantly located in the Tptll, and were not affected by rockfall. The number of key blocks predicted for Tptpll unit is minimal

(3 blocks per kilometer). For the Tptpll unit, only 1 percent of the drift length was affected by rockfall. For the Tptpln unit, only 3 percent of the drift length was affected by rockfall.

The seismic effects on rockfall were compared to the static key-block results. The comparison shows that there is an insignificant impact on the number of rockfalls for the 10^{-3} annual exceedance probability (peak ground acceleration of 0.14 g), and only a minor impact for both the 2×10^{-4} and 10^{-5} annual exceedance probabilities.

Because backfill is part of the EBS during the post-closure period, backfill was included in the drift-degradation analysis for the consideration of time-dependent and thermal effects. It is apparent that the blocks that form around the tunnel springline area will no longer occur in the analysis with backfill. Only minor increases of key blocks are predicted between year 200 and year 2,000. No change is predicted from year 2,000 to year 10,000.

The results indicate that seismic, time-dependent, and thermal effects have a relatively minor influence on rockfall. The LADS design for the repository is Enhanced Design Alternative II (CRWMS M&O 1999d, p. 4-16 and 4-17), which includes a drip shield and backfill. The presence of these design features precludes mechanical degradation or collapse of drift as a credible scenario contributing to waste-package failure. Because the thermal and seismic impacts on drift degradation are minimal, mechanical degradation or collapse of drift is *Exclude* from the TSPA based on low consequence. Secondary FEPs (see *YMP FEP Database*), including the impact of rockfall along fault areas (FEP No. 2.1.07.02.03) and the impact of accumulated blocks and rubble around the waste package (FEP No. 2.1.07.02.04) are also *Exclude* for these reasons.

Because the base-case rockfall scenario is minimal, thermal and seismic impacts on rockfall are minimal, and the design elements include a drip shield and backfill that will minimize any rockfall that will occur, there is no mechanism for creating significant damage to the waste package. Because the waste-package damage in minimized, there is no mechanism that would result in a release of radionuclides from the waste package, and calculated dose is not significantly changed. Consequently, mechanical degradation of the drift is *Exclude* from the TSPA based on low consequence.

6.2.19 Changes in Stress (due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock (2.2.06.01.00)

FEP Description: Changes in stress due to all causes, including heating, seismic activity, and regional tectonic activity, have a potential result in strains that affect flow properties in rock outside the excavation-disturbed zone.

Screening Decision: *Exclude*

Screening Decision Basis: Low Consequence

Screening Argument: The disposition of this FEP is more fully addressed in the *YMP FEP Database* (1999b).

Changes in stresses, regardless of the proximal cause, may result in changes to fracture hydrologic characteristics, as expressed through the parameter of fracture aperture. The effects of changes to the fracture system due to geologic effects on mountain-scale flow and radionuclide transport have been investigated using a sensitivity-analysis approach in *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b). The effect of changes in fracture apertures were examined because several fracture properties (permeability, capillary pressure, and porosity) are a function of fracture aperture. The results indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture. Therefore, effects on the unsaturated zone are *Exclude* based on low consequence.

The effect of stress on emplacement drifts from dike propagation is examined in *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000h, Section 6.3.2), which indicates that the effects are localized, perhaps up to 3 drift diameters from the drift. Stress along drifts resulting from fault displacement has been analyzed in *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GE-000004 (CRWMS M&O 2000f). The analysis indicates that stresses from fault displacements (which is the basis for the analysis in CRWMS M&O 2000b) are transmitted significant distances from the location of the fault. However, these stresses are of low consequence as discussed above.

TSPA Disposition: "Changes in stress change porosity and permeability of rock" and the associated Secondary FEPs are excluded as described under the Screening Argument. The disposition of this FEP is more fully addressed in the *YMP FEP Database*

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: None

Analysis and Discussion: See the *YMP FEP Database* regarding the following FEPs:

<u>Basis of excluding tectonic or regionally-induced stress changes:</u>

1.2.02.01.00 Tectonic Activity - Large Scale (also in this document Section 6.2.1)

<u>Discussion of excavation-related stress change:</u>

2.2.01.01.00, "Excavation and construction-related changes in the adjacent host rock"

2.2.01.02.00, "Thermal and other waste and Engineered Barrier System (EBS) related changes in the adjacent host rock"

Discussions regarding thermo-mechanical-related stress changes.

2.2.10.04.00, "Thermo-mechanical alteration of fractures near repository"

2.2.10.05.00, "Thermo-mechanical alteration of rocks above and below the repository"

6.2.20 Change in Stress (due to Thermal, Seismic, or Tectonic Effects) Produces Change in Permeability of Faults (2.2.06.02.00)

FEP Description: Stress changes due to thermal, tectonic and seismic processes result in strains that alter the permeability along and across faults.

Screening Decision: *Exclude*

Screening Decision Basis: Low Consequence

Screening Argument: Changes in stresses, regardless of the proximal cause, may result in changes to fracture hydrologic characteristics, as expressed in the parameter of fracture aperture. The effects of changes to the fracture system due to geologic effects on mountain-scale flow and radionuclide transport have been investigated using a sensitivity-analysis approach in *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000b). The effect of changes in fracture apertures were examined because several fracture properties (permeability, capillary pressure, and porosity) are functions of fracture aperture (CRWMS M&O 2000b, Section 6.2.2.3). The results indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture (CRWMS M&O 2000b, Section 7). Therefore, seismic effects on the unsaturated zone are *Exclude* based on low consequence.

Gauthier et al. (1996, p. 163 - 164) have analyzed the potential effects of seismic activity on contaminant transport in the SZ due to changes in water-table elevation. Their analysis indicates that the greatest strain-induced changes in water-table elevation occur with strike-slip faults. Simulations of the timing, magnitude and duration of water-table rise indicate a maximum rise of 50 meters within an hour of the simulated event. The simulated system returns to steady-state conditions within 6 months. Gauthier et al. (1996, pp. 163-164) concluded that:

> In general, seismically induced water-table excursions caused by poroelastic coupling would not influence the models presently being used to determine long-term performance of a repository at Yucca Mountain; therefore, we excluded them from the total-system simulations.

Alternative perspectives on seismic pumping and water-level changes are discussed in the Draft Environmental Impact Statement (DOE 1999, p. 3-49).

TSPA Disposition: Changes in Stress Produce Changes in Permeability of Faults and the associated Secondary FEPs are *Exclude* as described under the TSPA Disposition.

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: None

Analysis and Discussion: See Screening Argument

6.2.21 Changes in Stress (due to Seismic or Tectonic Effects) Alter Perched Water Zone (2.2.06.03.00)

FEP Description: Strain caused by stress changes from tectonic or seismic events alters the rock permeabilities that allow formation and persistence of perched-water zones.

Screening Decision: *Exclude*

Screening Decision Basis: Low Consequence

Screening Argument: This FEP is fully discussed in *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000i).

It seems unlikely that a change in stress could, in itself, adequately seal a zone such that perched water develops. The potential to release perched water as a result of stress changes and fracture openings, as a result of seismic activity, however is considered and hypothetically could result in a relatively sharp "pulse" of radionuclides, if perched water contained radionuclides, and if the perched water were allowed to drain below the repository.

The relatively small amount of water *in the fracture domain* below the potential repository, and the radionuclides that could be contained in this water, however, is not expected to cause a significant "pulse" in radionuclide mass flux at the water table. Consequently, this FEP is *Exclude* on the basis of low consequence. (see *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001: CRWMS M&O 2000i), Section 6.7.9) for a more detailed explanation.

TSPA Disposition: Changes in stress Alter Perched Water Zone and the associated Secondary FEPs are *Exclude* from the TSPA as described under the Screening Argument. This FEP is fully discussed in *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000i).

IRSR-Issues: Undetermined: to be updated for REV 01

Related AP-3.10Q: *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000i)

Analysis and Discussion: *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000i)

7. CONCLUSIONS

Table 3 provides a summary of the Tectonic FEP screening decisions and the basis for "*Exclude*" decisions. Shaded FEPs are Primary; others are Secondary. Not all Secondary FEPs are shown in Table 3 because many of the Secondary FEPs are redundant or Secondary FEP descriptions are insufficient to allow resolution.

This document and its conclusions may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confimation activites will be reflected in subsequent revisions. The status of the input information quality may be confirmed by review of the Document Input Reference System Database.

One of the Screening Decisions is listed as *Exclude* TBV for waste packages. This FEP deals with the potential for seismic damage to waste packages. For FEP 1.2.03.02.00, "Seismic vibration causes container failures", the Screening Decision is TBV because the current arguments, although supporting an *Exclude* decision, are qualitative in nature and are not conclusive. Consequently, additional verification of the effectiveness of the design and fragility of the waste package with respect to low-probability, high-energy seismic events is required. It is recommended that that verification of this Screening Decision be performed as part of waste-package design analysis or evaluated by the TSPA subject-mater experts who are addressing seismic damage effects.

Table 3. Summary of Disruptive Events FEPs Screening Decisions

YMP FEP Database Number	FEP Name	Screening Decision	Screening Basis
1.2.01.01.00	Tectonic activity—large scale	*Exclude*	Low Consequence
1.2.01.01.01	Folding, uplift of subsidence lowers facility with regard to current water table	*Exclude*	Low Consequence
1.2.01.01.02	Tectonic changes to local geothermal flux causes convective flow in SZ and elevates water table	*Exclude*	Low Probability
1.2.01.01.03	Tectonic folding alters dip of tuff beds, changing percolation flux	*Exclude*	Low Consequence
1.2.01.01.04	Uplift or subsidence changes drainage at the site, increasing infiltration	*Exclude*	Low Consequence
1.2.01.01.08	Uplift and subsidence	*Exclude*	Low Consequence
91.2.02.01.00	Fractures	*Include*: existing characteristics / *Exclude*: changes to characteristics.	Low Consequence
1.2.02.02.00	Faulting	*Include*: existing characteristics/ *Exclude*: changes in fault properties.	*Exclude*d based on low consequence, and low probability
1.2.02.02.05	Faulting/Fracturing	*Include*	
1.2.02.02.08	Normal faulting occurs or exists at Yucca Mountain	*Include*	
1.2.02.02.09	Strike/slip faulting occurs or exists at Yucca Mountain	*Include*	

Table 3. Summary of Disruptive Events FEPs Screening Decisions (continued)

YMP FEP Database Number	FEP Name	Screening Decision	Screening Basis
1.2.02.02.10	Detachment faulting occurs or exists at Yucca Mountain	*Exclude*	Low Consequence
1.2.02.02.11	Dip/slip faulting occurs at Yucca Mountain	*Include*	
1.2.02.02.12	New fault occurs at Yucca Mountain	*Exclude*	Low Consequence
1.2.02.02.13	Old fault strand is reactivated at Yucca Mountain	*Exclude*	Low Consequence
1.2.02.02.14	New fault strand is activated at Yucca Mountain	*Exclude*	Low Probability
1.2.02.03.00	Fault movement shears waste container	*Exclude*	Low Probability
1.2.03.01.00	Seismic activity (Note: Includes faulting, hydraulic heads, recharge-discharge zones, rock stresses, drift integrity)	*Exclude* for indirect effects / *Include* for drip shield and fuel-rod cladding damage	Low Consequence
1.2.03.02.00	Seismic vibration causes container failure	*Exclude* TBV for waste package / *Include* for drip shield and fuel-rod cladding.	Low Consequence
1.2.03.02.01	Container failure induced by microseisms associated with dike emplacement	*Exclude* TBV	Low Consequence
1.2.03.03.00	Seismicity associated with igneous activity	*Exclude* for indirect effects / *Include* for drip shield and fuel-rod cladding damage	Low Consequence
1.2.04.01.00	Igneous activity (Note: Also effects on faults, topography, rock stresses, groundwater temperatures & drift integrity)	*Include*: for direct effects / *Exclude*: for indirect effects	Low Consequence of Indirect Effects
1.2.04.02.00 *	Igneous activity causes changes to rock properties	*Exclude*	Low Consequence
1.2.04.02.01	Dike provides a permeable flow path	*Exclude*	Low Consequence
1.2.04.02.02	Dike provides a barrier to flow	*Exclude*	Low Consequence
1.2.04.02.03	Volcanic activity in the vicinity produces an impoundment	*Exclude*	Low Consequence
1.2.04.02.06	Dike related fractures alter flow	*Exclude*	Low Consequence
1.2.04.03.00	Igneous intrusion into repository	*Include*	
1.2.04.03.03	Sill intrudes repository openings	*Include*	
1.2.04.04.00	Magma interacts with waste	*Include*	
1.2.04.04.01	Magmatic volatiles attack waste	*Include*	
1.2.04.04.02	Dissolution of spent fuel in magma	*Include*	
1.2.04.04.03	Dissolution of other waste in magma	*Include*	
1.2.04.04.04	Heating of waste container by magma (without contact)	*Include*	
1.2.04.04.05	Failure of waste container by direct contact with magma	*Include*	
1.2.04.04.06	Fragmentation (Note: with subsequent damage to WP)	*Include*	
1.2.04.05.00	Magmatic transport of waste	*Exclude* for transport in liquid magma and	Low Consequence

Table 3. Summary of Disruptive Events FEPs Screening Decisions (continued)

YMP FEP Database Number	FEP Name	Screening Decision	Screening Basis
		other types of transport. / *Include* for transport through eruptive events	
1.2.04.05.01	Direct exposure of waste in dike apron	*Exclude*	Low Consequence
1.2.04.05.02	Volatile radionuclides plate out in the surrounding rock	*Exclude*	Low Consequence
1.2.04.05.03	Entrainment of SNF in a flowing dike	*Exclude*	Low Consequence
1.2.04.06.00	Basaltic cinder cone erupts through the repository (Note: Also entraining waste)	*Include*	
1.2.04.06.01	Vent jump (formerly called “wander”)	*Include*	
1.2.04.06.02	Vent erosion	*Include*	
1.2.04.07.00	Ashfall	*Include*	
1.2.10.01.00 *	Hydrologic response to seismic activity	*Exclude*	Low Consequence
1.2.10.02.00	Hydrologic response to igneous activity (Note: Includes groundwater flow directions; water level, chemistry, temperature; change in rock properties)	*Exclude*	Low Consequence
1.2.10.02.01	Interaction of WT (water table) with magma	*Exclude*	Low Consequence
1.2.10.02.02	Interaction of Unsaturated Zone pore water with magma	*Exclude*	Low Consequence
2.1.07.01.00	Rockfall (large block)	*Exclude*	Low Consequence
2.1.07.01.01	Rockbursts in container holes	*Exclude*	Low Consequence
2.1.07.02.00	Mechanical degradation or collapse of drift	*Exclude*	Low Consequence
2.1.07.02.03	Rockfall stopes up fault	*Exclude*	Low Consequence
2.1.07.02.04	Rockfall (rubble)(in waste and EBS)	*Exclude*	Low Consequence
2.2.06.01.00 *	Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock	*Exclude*	Low Consequence
2.2.06.02.00 *	Changes in stress (due to thermal, seismic, or tectonic effects) produces change in permeability of faults	*Exclude*	Low Consequence
2.2.06.03.00 *	Changes in stress (due to seismic or tectonic effects) alter perched water zones)	*Exclude*	Low Consequence

Notes: Shaded Items are Primary FEPs; others are Secondary FEPs
* These FEPs are addressed by multiple FEP AMRs , see the YMP FEP Database (1999b)

8. REFERENCES

This document contains citations to draft documents currently in development. All such cited reference documentation must be completed and approved before this document can be approved. All such draft citations must be resolved or removed before completion of this document. (per Style Manual August 1999, Section 13.1)

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8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

64 FR 46976. 40 CFR 197: Environmental Radiation Protection Standards for Yucca Mountain, Nevada; Proposed Rule. Readily Available

64 FR 8640. Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada. Proposed rule 10 CFR 63. Readily Available

AP-3.10Q, REV. 2, ICN 0. *Analyses and Models.* Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL. 20000217.0246.

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ATTACHMENT I
GLOSSARY

aperture - The gap between two wall or faces of a fracture.

asperity - An area of contact between two surfaces of a fracture.

background earthquake - An earthquake that does not produce ground breakage, and hence not associated with a known fault. Such earthquakes are considered to be random in time and space. In the Great Basin, background earthquakes have magnitudes less the 6.0.

basalt - A dark-colored fine-grained rock formed by volcanism or dike or sill intrusion; consists chiefly of calcic plagioclase, pyroxene and olivine.

base level - The theoretical lowest level toward which erosion progresses, considered practically as the level below which a stream cannot erode its bed.

blind fault - A fault that dies out in bedrock and is not exposed at Earth's surface.

block faulting - Segmentation of the crust into block-like masses by systematic normal faulting.

caldera complex - An assemblage of extrusive and intrusive rocks and associated structures generated by explosive and effusive volcanism that comprise a number of genetically related overlapping or adjacent or proximal calderas.

caliche - A calcareous soil component typically forming a friable to hard, off-white, crudely layered interval near the surface of stony desert soils; several cm or more thick; old, thick caliche intervals (calcrete) have the texture and hardness of concrete aggregate.

colluvial slope - A hill slope mantled with loose, heterogeneous soil and rock fragments which are the result of weathering and accumulation by creep and unchanneled snow melt or runoff.

conduit - The vertical or subvertical, essentially cylindrical, tube that brings magmatic material to the surface. Conduit is the appropriate term regarding the subsurface, and PA conceptual models emphasize the interactions that occur at the intersection of a conduit with the repository.

Crater Flat tectonic domain - A tectonic domain is a block of the Earth's crust bounded by major faults or zones of complex shear and deformation. A domain features a history and styles of deformation that distinguish it from adjacent areas of the crust. The Crater Flat domain includes Yucca Mountain and is characterized by normal faulting into Crater Flat basin.

critical group - A theoretical group of individuals, based on observed population characteristics, which reside within a farming community located approximately 20 km south from the underground facility (in the general location of U.S. route 95 and Nevada Route 373, near Lathrop Wells, Nevada).

debris flow - A moving mass of rock fragments and mud, most fragments larger than sand size; water-mobilized colluvium; also the deposit of such a flow.

detachment faulting - A style of normal faulting wherein large displacement occurs on a fault plane that dips less than 30°. In places the lower plates (footwalls) of detachment faults have been uplifted from mid crustal depths, implying that detachment is accompanied by significant isostatic uplift or uplift by magmatic inflation.

dike - A tabular intrusion of magma that is at a high angle to layering in the intruded strata (i.e., vertical or subvertical at Yucca Mountain).

dike system - One or more dikes that are closely related in space and time. Dike systems may include multiple dikes that share a common magmatic source with a single volcano. This definition does not preclude the possibility that a dike system may feed more than one volcano.

dip-slip faulting - Faulting in which the hanging wall moves down the dip of the fault plane. Normal faulting has slip directly along the dip normal to the strike of the fault, oblique faulting has a component of slip parallel to the fault strike (i.e., some lateral displacement).

disruptive FEP - An *Include* FEP that has a probability of occurrence during the period of performance less than 1.0 (but greater that the cutoff of $10^{-4}/10^{4}$year).

disruptive scenario - Any scenario that contains all expected FEPs and one or more disruptive FEPs.

eruptive event (with respect to repository performance) - The formation of a volcano that includes at least one subsurface conduit that intersects a drift containing waste packages.

event - A natural or anthropogenic 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.

expected FEP - An included FEP that, for the purposes of the TSPA, is assumed to occur with a probability equal to 1.0 during the period of performance.

extrusive event (with respect to repository performance) - Synonymous with eruptive event.

faulting - Process of fracture and attendant slip along the fracture plane, or recurrent slip along a such a plane.

fault strand - A fault segment expressed as a continuous intersection with the earth's surface, as indicated by a scarp, scarp line, or series of exposed displacement features, all having the same style of offset.

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

folding - Formation of folds expressed by geometric features that include fold limbs, fold axes, and axial planes. Large or systematic compressive and drag folds are results of tectonic activity.

fracture - A brittle crack in rock. Groups of fractures in more or less regular orientation and spacing are joints. Fractures form by bending (shear joints) or tension or principal stress reduction (extension joints). Cooling joints are formed by tension exerted by contraction as a volcanic rock cools.

future - A single, deterministic representation of the future state of the system. An essentially infinite set of futures can be imagined for any system.

geodetic strain rate - Regional strain rate determined at the earth's surface by repeated measurement of displacements of precisely located landmarks (monuments) embedded in the deforming medium.

geothermal gradient - The rate of increase of temperature in the Earth with depth.

heat flow - The amount of heat energy leaving the earth's crust, measured in HFU or calories/m^2/sec.

igneous activity - Any process associated with the generation, movement, emplacement, or cooling of molten rock within the earth or exterior to the earth's surface.

included FEP - A FEP that is identified by the FEP screening process as requiring analysis in the quantitative TSPA.

intrusive event (with respect to repository performance) - An igneous intrusion (such as a dike, dike system, or other magmatic body in the subsurface) that intersects the repository footprint at the repository elevation.

key block - Critical blocks formed in the surrounding rock mass of an excavation (by the intersection of three or more planes of structural discontinuity) which are removable and oriented in an unsafe manner so that they are likely to move into the opening unless restraint is provided.

lithophysa - A subrounded cavity from about one to several cm in diameter formed in silicic volcanic rocks (e.g., welded tuff) by gas bubbles evolved during cooling; lithophysae are typically lined or largely filled with finely crystalline or cryptocrystalline rinds of secondary vapor-phase minerals.

magma - Partially or completely molten rock within the earth's crust or mantle.

magmatic inflation - Uplift of the crust caused by intrusion of subjacent magma, either large-volume batholithic melts, dike swarms, or lower crustal magmatic underplating.

mantle - The zone of the Earth below the crust and above the core, typified by high seismic velocity and dense iron and magnesium-rich silicate mineral components.

mantle plume - A large mass of molten mantle material rising up from the lower mantle into the base of the crust by process of convection and buoyancy; plumes are typically 100s of km in area.

Miocene - Epoch of the Tertiary Period between 24 Ma and 5 Ma.

nominal scenario - The scenario that contains all expected FEPs and no disruptive FEPs.

nonwelded unit - A volcanic ash, or tuff, that is crumbly or easily excavated because the component glass shards did not weld together during compaction of relatively cool ash, or ash having relatively sparse glass content.

paleoseismic slip - The amount of fault slip indicated by buried offset strata; individual paleoearthquakes are indicated by discrete amounts of offset.

percolation flow - Flow of groundwater through small, interconnected rock or soil pores.

playa - A dried lake bed, typically a flat, salty surface that forms the low part of a confined desert basin.

Pleistocene - The epoch of the Quaternary Period from about 1.6 Ma to about 10 ka.

Plio-Pleistocene - Combined duration of the Pliocene and Pleistocene epochs of the Cenozoic era, from 5 Ma to 10 ka.

potentiometric surface - A notional surface representing the total head of groundwater as defined by the level such water stands in a well; the water table is a particular potentiometric surface.

process - A natural or anthropogenic phenomenon that has a potential to affect disposal system performance and that operates during all or a significant part of the period of performance.

pumice - Highly vesicular or frothy siliceous glass formed during volcanic eruption; typically a pale gray color.

pumiceous - Having observable pumice content.

Quaternary - The period of the Cenozoic Era from 2.6 Ma to present; includes the Pleistocene and Holocene Epochs.

rockburst - A sudden and often violent failure of masses of rocks in quarries, tunnels, or mines.

rollover - A steepening of dip in the downthrown block of a normal fault as the fault plane is approached.

regional slope - The slope of a surface defined by contouring the elevations of resistant peaks in a given area; it approximates the surface formed by uplift prior to erosional incision.

regional subsidence - Broad depression of the earth's surface resulting from tectonic activity such as extension, crustal cooling, or deep crustal or mantle flow.

regional uplift - Broad elevation of the earth's surface resulting from tectonic activity such as compression or igneous intrusion.

rockburst - Uncontrolled disruption of rock associated with a violent release of energy additional to that derived from falling rock fragments.

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

seismic activity - Seismicity; the recurrence and distribution of earthquakes associated with a specified seismic source.

seismicity - The capacity of a fault, group of faults, or region of the crust to generate earthquakes, as determined by instrumental or paleoseismic history; the relative rate at which earthquakes recur (syn. seismic activity).

springline - The imaginary line at which an arch or vault begins to curve; for circular cross-sections, this corresponds to the mid-point along the drift wall.

stoping – In the FEPs context, this term is used to mean the progressive, generally upward, breaking and removal of rock along a drift, fracture, fault, or other feature due to natural causes.

strain rate - The rate at which a unit of length is shortened or lengthened under a stress load, usually given in terms of [T^{-1}] in seconds. Strain rate is often expressed in units of mm/yr where an actual length difference rather than a ratio is calculated.

strand - A fault strand is generally taken to connote a relatively short fault segment or "splay" that is one of a series of many faults that together form the principal fault zone. The zone is usually not straight and well developed, and faults may bifurcate or anastomose or step over from one fault to another. Slip can be transferred across many strands.

stream gradient - Angle between inclination of a stream channel bed and the horizontal measured in direction of flow (i.e., the “slope” of a stream).

subducting slab - A section of oceanic (basaltic) crust in process of being drawn down into the upper mantle by subduction.

tectonic activity - The dynamic manifestation of stress loads generated within the earth’s crust (e.g., igneous intrusion, earthquakes, uplift).

tectonic deformation - The suite of geological structures generated by body stresses exerted within the earth’s crust; such structures range in scale from microscopic (e.g., mylonite fabric) to regional (e.g., overthust belts). Also, the process by which such structures together are formed.

tectonic extension - Stretching or extension of the crust as a result of deep-seated tectonic stress, such as back-arc spreading.

tectonic process - The dynamic evolution of structure generated through the buildup and relaxation of regional stress.

tectonism - All movement of the crust at small scale produced by tectonic processes, including mountain building (orogeny), regional uplift and subsidence; the general expression of tectonic process through time and space.

terrain relief - Relief of some defined area of the earth’s surface as the measure of difference between the lowest local elevation and the highest local elevation.

Type I fault - Faults or fault zones that are subject to displacement and are of sufficient length and location such that they may affect repository design or performance.

vent - The intersection of a conduit with the land surface. Volcanoes may have more than one vent.

vertical axis rotation - Folding referenced to a vertical axis of folding. Hence, beds or layers change strike around the inferred vertical axis.

volcanic activity - The suite of events and processes associated with extrusion of molten rock, such as eruption, lava emission, cone formation; the subaerial components of igneous activity.

volcanic event - The formation of a volcano (with one or more vents) resulting from the ascent of basaltic magma through the crust as a dike or system of dikes.

volcano - A geologic feature than includes an edifice of magmatic material erupted on the land surface, one or more conduits that feed the eruption, and a dike or dike system that feed the conduit or conduits.

water table - The surface of unconfined groundwater at which the pressure is equal to that of the atmosphere.

welded unit - A volcanic ash, or tuff, that is strongly indurated because hot glass shards partially melted together (welded) during compaction of the ash bed while the ash was still hot.