OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL COVER SHEET

Complete Only Applicable Items

1. QA: QA

2. X Analysis Check all that apply		3. ☐ Model Check all that apply	
Type of Analysis	☐ Engineering X Performance Assessment ☐ Scientific	Type of Model	☐ Conceptual Model ☐ Abstraction Model ☐ Mathematical Model ☐ System Model ☐ Process Model
Intended Use of Analysis	☐ Input to Calculation ☐ Input to another Analysis or Model ☐ Input to Technical Document X Input to other Technical Products	Intended Use of Model	☐ Input to Calculation ☐ Input to another Model or Analysis ☐ Input to Technical Document ☐ Input to other Technical Products
Describe use: This AMR is intended to summarize the decision, arguments, and disposition of features, events, and processes (FEPs) in the TSPA-SR.		Describe use:	

4. Title:
Features, Events, and Processes: Disruptive Events

5. Document Identifier (including Rev. No. and Change No., if applicable):
ANL-WIS-MD-000005 REV 00 ICN 1

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- Bill Arnold - PA - SZ flow issues
- Scott Bennett - WPD - Waste package and design-related FEPs
- Jim Houseworth - UZ - UZ flow issues and fracture-related FEPs
- Dwayne Kicker - Repository Modeling - Rockfall-related FEPs
- Dennis O'Leary - USGS - Faulting-related and tectonic-related FEPs
- Carl Stepp - Site Integration - Tectonic-related, faulting-related, and seismic-related FEPs
- Greg Valentine - Site Integration - Igneous-related natural site analogues

Title change from REV 00.

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Enclosure 2

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD

Complete Only Applicable Items

2. Analysis or Model Title:

Features, Events, and Processes: Screening for Disruptive Events

3. Document Identifier (including Rev. No. and Change No., if applicable):

ANL-WIS-MD-000005 REV 00 ICN 1

4. Revision/Change No.	5. Description of Revision/Change
00	Initial Issues
REV 00 ICN 1	This ICN addreses FEP screening for the no backfill design and drift reorientation. Also, screening arguments include a statement of the potential consequence of the FEP to clarify arguments. Table 3 (now Table 4) has been expanded to include all Secondary FEPs for the Primary FEPs of interest. Attachment II has been added to show relationships and traceability from the secondary FEPs to the Primary FEPs, to provide mapping of the FEPs to KTI Subissues and to Integrated Subissues, and to show relationships to other non-Disruptive Events FEPs. This ICN is being issued in its entirely due to the number of effected pages.

CONTENTS

CONTENTS (continued)

TABLES

ATTACHMENTS

ACRONYMS AND ABBREVIATIONS

Acronyms

AMR	Analysis Model Report
AP	Administrative Procedure
CFR	Code of Federal Regulations
CRWMS	Civilian Radioactive Waste Management System
DOE	Department of Energy
DRKBA	Discrete Regional Key Block Analysis
EBS	Engineered Barrier System
ECRB	Enhanced Characterization of the Repository Block
EPA	Environmental Protection Agency
ESF	Exploratory Studies Facility
FEP	Feature, Event, or Process
FR	Federal Register
ICN	Interim Change Notice
IRSR	Issue Resolution Status Report
ISI	Integrated Subissue
KTI	Key Technical Issue
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

ACRONYMS AND ABBREVIATIONS (continued)

Acronyms

RMEI	Reasonably Maximally Exposed Individual
SZ	Saturated Zone
T1, T2, . . .	Technical Acceptance Criteria
TBV	To Be Verified
TSPA	Total System Performance Assessment
TSPAI	Total System Performance Assessment and Integration
TSPA-SR	Total System Performance Assessment-Site Recommendation
UDEC	Universal Distinct Element Code
USGS	United States Geological Survey
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
MT	metric ton (or tonne)
MTU	metric ton uranium
Mw	moment magnitude (a measure of earthquake magnitude)
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 nonlithophysal
yr	year

1. PURPOSE

The primary purpose of this Analysis/Model Report (AMR) is to document the screening analyses for each of the 21 features, events, or processes (FEPs) designated as Disruptive Events Primary FEPs and listed in Section 1.1. This AMR (ANL-WIS-MD-000005) documents the Screening Decision and Regulatory Basis, the Screening Argument, and the Total System Performance Assessment (TSPA) Disposition for each of the Disruptive Events Primary FEPs. This AMR provides screening information and decisions for the Disruptive Events Process Model Report (PMR) and provides the same information for a project-specific FEPs database. This AMR may also assist reviewers during the licensing-review process.

This AMR was originally issued (REV 00) based on consideration of a repository with backfill and drip shields, as described in the *License Application Design Selection Report* (CRWMS M&O 1999a, EDA II). This AMR now also addresses the no-backfill repository design. On January 26, 2000, a design change was initiated to resolve certain thermal design issues. This design change was described in Technical Change Request T2000-0133, dated January 26, 2000 (CRWMS M&O 2000a). Additional design changes were noted in "Repository Subsurface Design Information to Support TSPA-SR," PA_SSR-99218.Tc (CRWMS M&O 2000b). These design considerations included reorienting the emplacement drifts to azimuth 252/72, removing the backfill from the design, and considering repository layouts/relocations to accommodate both a 70,000-metric-ton uranium (MTU) and 97,000-MTU design.

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), and also NRC's proposed rule 10 CFR 63 (64 FR 8640), the DOE must provide a reasonable assurance that the performance objectives for the Yucca Mountain Project (YMP) can be achieved for a 10,000-year postclosure period. This assurance must be demonstrated in the form of a performance assessment that (1) identifies the 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 bases for inclusion or exclusion of specific FEPs from the performance assessment.

Although not defined or specified in DOE's Interim Guidance (Dyer 1999) or the NRC's proposed rule 10 CFR 63 (64 FR 8640), YMP 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 *Included* in the Total System Performance Assessment - Site Recommendation (TSPA-SR) or *Excluded* from the TSPA-SR (see Section 1.3).

1.1 SCOPE

This AMR satisfies 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 1999b).

The current FEPs list for YMP consists of 1,797 entries, classified as Primary and Secondary FEPs (as described in Section 1.2). Based on the nature of the FEPs, they have been assigned to various Process Model Reports (PMRs), so that the analysis and disposition for each FEP resides with the subject-matter experts in the relevant disciplines. The disposition of FEPs other than Disruptive Events FEPs is documented in AMRs and PMRs prepared by the responsible PMR groups. Several relevant FEPs do not fit neatly into the existing PMR structure. Some FEPs were best assigned to the TSPA itself (i.e., System-Level FEPs), rather than to its component models. An example is criticality, which is treated in FEP assignments as if it were a separate subset of FEPs and is included in the System-Level FEPs report (ANL-WIS-MD-000005) along with the remaining System-Level FEPs.

In the original FEP assignments, 26 FEPs were originally designated as Disruptive Events Primary FEPs. Five of the FEPs were subsequently reassigned (see Section 1.2) to the System-level FEPs AMR (ANLW-WIS-MD-000019). This AMR (ANL-WIS-MD-000005) addresses the 21 Primary FEPs that have been identified as Disruptive Events FEPs and assigned to this AMR. The 21 Disruptive Events Primary FEPs addressed in this AMR are identified in Table 1.

These 21 Primary FEPs represent natural-system processes that have the potential to produce a disruptive event. A disruptive event is defined as an "*Included* in the TSPA-SR" FEP that has a probability of occurrence during the period of performance less than 1.0 but greater than the probability screening criterion of one chance in 10,000 in 10,000 years ($10^{-4}/10^{4}$ yr). These 21 Primary FEPs are related to geologic processes such as structural deformation, seismicity, and igneous activity. Of the 21 Disruptive Events Primary FEPs, 16 are addressed explicitly and fully in this AMR. The remaining five Disruptive Events Primary FEPs are addressed in this AMR 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 the remaining five FEPs have significant overlap to the related subject areas and are better discussed in the context of the referenced AMR.

Table 1. Disruptive Events Primary 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

Table 1. Disruptive Events Primary FEPs (continued)

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

1.2 FEPs IDENTIFICATION AND CLASSIFICATION

The YMP TSPA has chosen to satisfy the performance-assessment requirements by adopting a scenario-development process. 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 2000c, Appendix D).

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 2000c, Appendix D) contains 1,797 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
- YMP-specific FEPs identified in FEP AMRs
- YMP-specific FEPs identified by external review (the NRC)

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 1,261 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 1990); 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 1,261 FEPs identified by these programs have been organized by the NEA FEP database working group into a hierarchical structure that is defined by 151 layers, categories, and headings. The *YMP FEP Database* uses the same structure as the NEA FEP database (see Section 1.4). Each of the layers, categories, and headings is an individual entry in the *YMP FEP Database*, as are the 1,261 FEPs, which are organized under them. Therefore, the *YMP FEP Database* contains a total of 1,412 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 represented events and processes not otherwise included in the international compilation. The supplemental entries resulted from a search of YMP literature in 1998 that identified 292 additional FEP entries. Relevant FEPs from the 1,704 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. A second round of reviews by subject-matter experts was performed in 1999 and 2000 in association with the development of FEP AMRs. During the preparation of the FEP AMRs, subject-matter experts reviewed the existing FEPs relevant to their subject area and, where necessary, identified new or missing FEPs. This review and documentation process identified nine additional FEPs

An interim version of the YMP FEP list was provided to the NRC in association with the NRC/DOE Appendix 7 Meeting on the FEPs Database held September 8, 1999. A subsequent NRC audit of this interim version of the YMP FEP list identified one potential FEP unrelated to any existing FEPs (Pickett and Leslie 1999, Section 3.3). The audit also identified three potential FEPs that were possibly related to existing FEPs. Two of these FEPs were subsequently determined to be redundant to or subsumed in existing FEPs. The other two FEPs were added to the YMP FEP list.

In summary, the *YMP FEP Database* (CRWMS M&O 2000c, Appendix D) contains 1,797 entries, comprised of 151 layers, categories, and headings (which define the hierarchical structure of the database, as described in Section 1.4) and 1,646 specific feature, event, and/or process entries. 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.

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. 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. If the FEPs are too narrowly defined, the narrow definition may result in an otherwise relevant FEP being excluded based on "low probability" or "low consequence to dose" caused by the narrow definition. 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 further classified 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" is used to address multiple and redundant secondary FEPs that concern movement along faults of various scales, generation and formation of new faults, reactivation of old faults, and the various types and occurrences of faults in the Yucca Mountain area. Definitions for terms used in the FEPs descriptions and screening are provided in the Glossary in Attachment I. The relationships of the Primary FEPs to the Secondary FEPs are shown in the tables in Attachment II along with the Primary FEPs relationships to Key Technical Issues (KTIs) and Subissues and to Integrated Subissues (see NRC 1999a, 1999b, and 2000a). Attachment II also provides the relationships to other related Primary FEPs not addressed in this AMR.

To perform the screening and analysis, the FEPs have been assigned based on the PMR structure so that the analysis, Screening Decision, Screening Argument, 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 designated as Disruptive Events Primary 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 this AMR (ANL-WIS-MD-000005). Of the 21 Disruptive Events Primary FEPs, 16 are addressed explicitly and fully in this AMR. As previously stated, five of the Disruptive Events Primary FEPs are addressed explicitly and fully by other AMRs, and are addressed in summary form in this AMR. The five FEPs in question concern changes in rock properties due to seismic or igneous activity, or potential changes in hydrologic parameters due to changes in the stress field.

Prior to and during the FEP-screening process, the Primary and Secondary FEPs were reviewed: (1) to verify that the FEPs had been appropriately assigned to the Disruptive Events report; (2) to ensure that other FEPs (either previously identified or not-identified) were being addressed either in this or other FEP-related AMRs; and (3) to determine that all Secondary FEPs were appropriately included within the Primary FEP descriptions. Only one secondary FEP, "Faulting exhumes waste container," a secondary FEP to the Primary FEP "Faulting," was found not to be in the FEPs list and it was subsequently added to the FEPs list.

1.3 FEP-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 the project screening criteria. Each FEP is screened against the guidance, assumptions, or specific criteria stated in DOE's Interim Guidance (Dyer, 1999), NRC's proposed rule 10 CFR 63 (64 FR 8640), and the U.S. Environmental Protection Agency's (EPA) proposed rule 40 CFR Part 197 (64 FR 46976). 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 one chance in 10,000 in 10,000 years ($10^{-4}/10^{4}$ yr)?

- 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)

Based on the three screening criteria stated above, the FEP is either *Included* in the TSPA-SR or *Excluded* from the TSPA-SR. If the response to each of these screening criteria is "no," then the screening decision of the FEP is *Included* in the TSPA-SR because the FEP does not satisfy a screening criterion. Inclusion of a FEP in the TSPA-SR signifies that the potential effects of a

FEP on repository performance are specifically included in performance-related and dose-related calculations. In addition, 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. An expected FEP is a FEP that is *Included* in the TSPA-SR, and that for the purposes of the TSPA, is presumed to occur with a probability equal to 1.0 during the period of performance. A disruptive FEP is a FEP that is *Included* in the TSPA-SR, and that has a probability of occurrence during the period of performance of less than 1.0 but greater than the screening criteria of $10^{-4}/10^{4}$ yr. Exclusion of a FEP from the TSPA-SR signifies that the FEP satisfies one or more of the screening criteria listed above. In that case, the FEP is not modeled in the TSPA-SR.

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 *Included* in the TSPA-SR and some that are *Excluded* from the TSPA-SR. Or, in some situations, existing conditions (such as existing fracture characteristics) are *Included* in the TSPA-SR, but changes in conditions (such as changes in fracture aperture) have been demonstrated to be of no significance and are considered as *Excluded* from the TSPA-SR. In these situations, the screening decision will specify which elements are *Included* in the TSPA-SR and which are *Excluded* from the TSPA-SR. 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 designation of "*Excluded* from the TSPA-SR" will also specify the disposition as "Preliminary."

1.3.1 "Regulatory" Exclusion

The screening criteria contained in DOE's Interim Guidance (Dyer 1999), at proposed rule 10 CFR 63 (64 FR 8640), and at proposed rule 40 CFR Part 197 (64 FR 46976) are relevant to many of the FEPs. FEPs that are contrary to DOE's Interim Guidance, or to specific proposed regulations, regulatory assumptions, or regulatory intent are excluded from further consideration. Examples include: the explicit exclusion from consideration of all but a stylized scenario to address treatment of human intrusion (Dyer 1999, Section 113(d); 64 FR 8640, Section 113(d)); assumptions about the critical group to be considered in the dose assessment (Dyer 1999, Section 115; 64 FR 8640, 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).

1.3.2 "Low Probability" Exclusion

Probability estimates used in the FEP screening process are based on a technical analysis (either by consideration of bounding conditions or by 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 design elements to such events and processes.

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." The definition of process is "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." For probability considerations, the definitions of *event* and *process* may involve (1) the probability of the phenomenon occurring, and (2) the probability of affecting repository performance.

Consequently, probability screening may be considered on two bases. The first basis for the probability screening is the consideration of the probability of a phenomenon occurring independent of its effect on the repository. This is particularly germane to geologic processes where the phenomena are well defined. If it can be demonstrated that a phenomenon (independent of its effect on the repository) is of low probability, the phenomenon is excluded from the TSPA. For example, faulting of intact rock can be excluded based on low probability of significant displacement; therefore, the potential to affect the repository does not need to be further analyzed.

A second basis for the probability screening is invoked if an event is defined in terms of the behavior of the repository, rather than solely in terms of the behavior of the independent geologic phenomenon. This distinction is important for FEP screening because the interactions of the engineered repository and the geologic system over long periods of time make it difficult to distinguish uniquely between external events that are independent of the repository (i.e., the initiating events in the language of guidance and proposed regulations relevant to preclosure operations) and those that are dependent on the long-term evolution of the repository system. Therefore, a low-probability-screening argument may be used if it is shown that the specific behavior of the repository is of low probability, regardless of the probability of the various events that may have contributed to that behavior. For example, "Fault movement shears waste container" is excluded on low probability based on design features (the separation distance of the waste package and drift wall and the set-back distance from block-bounding faults) because the design features negate the effect of possible fault displacements. As a result, although fault displacements on existing faults (the geologic phenomenon) cannot be excluded on low probability, its effect on the repository (shears waste container) is excluded.

For this AMR, the words *damage*, *failure*, *breaching*, and *impairment* are used in a specific sense, as follows:

- *Damage* generically encompasses failure, breaching, or impairment of the drip shield, waste package, or other design element.

- *Failure* is defined respective to "performing the intended waste-containment function" and is used in the engineering sense of whether a design element meets a stated material property or performance measure. The term "failure" is correspondingly used with regard to rock properties in the sense of rock failure being the proximal cause of faults, fractures, or rockfall.

- *Breaching* is used to imply that radionuclide containment can no longer be presumed due to a penetration, rupture, or tear entirely through the waste package, or that protection of the waste package from dripping and seepage is no longer functional due to a penetration, rupture, or tear in the drip shield.

- *Impairment* is loosely defined as applying to other effects, such as accelerated degradation or corrosion rates or stress cracking, that shorten the performance lifetime.

If an event is defined in terms of the behavior of the repository, rather than solely in terms of the behavior of the independent geologic phenomenon, then the low-probability argument may also be a low-consequence-to-dose argument. That is, if no damage or impairment of engineered systems occurs, then there is no mechanism for release or accelerated release of radionuclides. Therefore, there is no significant change to dose, and the regulatory basis for exclusion is "low consequence to dose." For example, the repository design includes installation of drip shields. The FEP "Rockfall (large block)" is excluded based on the performance characteristics of the drip-shield design. Because the largest calculated rockfall does not breach the drip shield, the waste packages remain unaffected. As a result, the FEP "Rockfall (large block)" could be excluded either as a non-credible event (or "low probability"), or as "low consequence to dose" because "Rockfall (large block)" does not provide a mechanism to damage the waste package and ultimately increase the dose. The basis for a low-consequence-to-dose argument is discussed further in the following section.

1.3.3 "Low Consequence to Dose" Exclusion

The last of the three screening criteria stated in 1.3 above allows FEPs to be excluded from further consideration if there would be negligible change to the resulting expected annual dose. (i.e., on the basis of "low consequence to dose"). The terms "significantly changed" and "changed significantly" are used in the NRC's and EPA's proposed regulations but are undefined terms. 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." For FEP-screening purposes, these terms are inferred to be equivalent to having no, or negligible, effect.

The low-consequence-to-dose arguments are made for the FEP screening by demonstrating that a particular FEP has no effect on the distribution of an intermediate-performance measure in the TSPA. If a FEP can be shown to have negligible impact on unsaturated zone (UZ) or saturated zone (SZ) flow and transport, waste-package integrity, or other components of the engineered barrier system (EBS) or natural-barrier system, then the FEP does not provide a mechanism that results in an increase in the expected annual dose in the TSPA. In some cases, the demonstration maybe direct, using results of computer simulations of the potential event or process. 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 dose, 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.

In other cases, the low-consequence-to-dose argument may involve quantitative reasoning that considers probabilities that are less than preclosure-design events but that do not satisfy the probability screening criterion. When coupled with other factors that demonstrate minimal impact to the repository, it can be demonstrated that the minimal damage weighted by the probabilities would have a negligible impact on dose. The FEP can, therefore, be *Excluded* from the TSPA-SR based on "low consequence to dose."

Various means to demonstrate negligible impact include site-specific data; TSPA sensitivity analyses; expertise of the subject-matter experts (including, in some cases, the expert-elicitation process); natural analogues; modeling studies outside of the TSPA; and reasoned arguments based on literature research. More complicated processes, such as igneous activity, may require detailed analyses conducted specifically for the YMP.

1.4 ORGANIZATION OF YMP FEP DATABASE

Under a separate task, the TSPA team is constructing an electronic database, the *YMP FEP Database* (CRWMS M&O 2000c, Appendix D), that contains information related to the FEP Screening Decisions and Regulatory Bases, the Screening Arguments, and the TSPA Dispositions.

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* 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 FEP 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)
	2.2 Geologic Environment	14 (excavation-disturbed zone, rock properties, geosphere processes)
	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 Disruptive Events Primary FEPs are shown in Table 1 (Section 1.1) and are included in the report section headings under Section 6.2. Using this organization, the Secondary FEPs are appropriately placed under the Primary FEPs in the database structure.

2. QUALITY ASSURANCE

The Quality Assurance (QA) Program applies to the development of this analysis. The Performance Assessment Operations responsible manager has evaluated the technical-document-development activity in accordance with QAP-2-0, *Conduct of Activities*. The QAP-2-0 activity evaluation, *Conduct of Performance Assessment* (CRWMS M&O 1999c, WBS#13012130M2) has determined that the preparation and review of this technical document is subject to the *Quality Assurance Requirements and Description* (QARD) DOE-RW-0333P (DOE 2000) requirements. Although QAP-2-0 *Conduct of Activities* has been replaced by AP-2.21Q *Quality Determinations and Planning for Scientific, Engineering, And Regulatory Compliance Activities*, the QAP-2-0 activity evaluation (CRWMS M&O 1999c) remains in effect. Preparation of the analysis did not require the classification of items in accordance with QAP-2-3 *Classification of Permanent Items*. Because this activity is not a field activity, an evaluation in accordance with NLP-2-0 *Determination of Importance Evaluations* was not required.

The analysis activities documented in this AMR have been conducted in accordance with the Civilian Radioactive Waste Management System Management and Operating (CRWMS M&O) Contractor's quality-assurance program, using approved procedures identified in the Development Plan entitled *Evaluate/Screen Tectonics FEPs* (CRWMS M&O 1999b).

The methods used to control the electronic management of data as required by AP-SV.1Q *Control of the Electronic Management of Information* were not specified in the development plan entitled *Evaluate/Screen Tectonics FEPs* (CRWMS M&O 1999b). With regard to the development plan for the analysis, the control of electronic management of data was evaluated in accordance with YAP-SV.1 *Control of the Electronic Management of Data*. This evaluation (CRWMS M&O 2000d) determined that the current work processes and procedures are adequate for the control of electronic management of data for this activity. Though YAP-SV.1Q has been replaced by AP-SV-1.Q, this evaluation remains in effect.

The list of the 21 Disruptive Events Primary FEPs addressed in this AMR was derived from the *YMP FEP Database* REV 00 (CRWMS M&O 2000c, Appendix D). REV 00 of the FEPs database is currently scheduled as a Level 3 Milestone, deliverable to DOE as part of the TSPA-SR deliverables and will be maintained in accordance with AP-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 on other 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 FEP Screening Arguments and TSPA Dispositions is such that cited data and information 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 and information 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 and information. Consequently, the data and information are not listed as inputs in this section but are cited in the individual FEP Screening Arguments and TSPA Dispositions.

Because of its reliance on the below-mentioned AMRs and Calculations, this AMR and its conclusions may be affected by technical-product information that requires confirmation. Based on the TBV requirements as presented in AP-3.15Q, the information from the below-referenced AMRs is considered as "NA-Technical Product Output" for the purposes of this AMR. Screening Decisions that rely upon one or more of the "Technical Product Output" from the documents discussed below are labeled as "Preliminary" to denote that the Screening Decision is subject to later revisions, pending closure of TBV issues in the originating document(s). Resolution of the TBV items, however, is not expected to change the Screening Decisions discussed in Section 6.2.

Any changes to the conclusions of the source documents listed below that may occur as a result of completing the "To Be Verified" (TBV) confirmation activities to resolve the below-listed TBVs will be reflected in subsequent revisions. The status of the input-information quality may be confirmed by review of the Document Input Reference system (DIRs) database for the source documents.

For this AMR, the following six source documents use input data or provide conclusions that are based on TBV information:

- *Fault Displacement Effects on Transport in the Unsaturated Zone*, ANL-NBS-HS-000020 (CRWMS M&O 2000e)
- *Input Request for Seismic Evaluations of Waste Packages and Emplacement Pallets* (CRWMS M&O 2000f).
- *FEPs Screening of Process and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 (CRWMS M&O 2000g)
- *EBS Radionuclide Transport Abstraction* ANL-WIS-PA-000001 CRWMS M&O 2000h)
- *Drift Degradation Analysis* ANL-EBS-MD-000027 (CRWMS M&O 2000i)
- *Supporting Rock Fall Calculation for Drift Degradation: Drift Reorientation with No Backfill* CAL-EBS-MD-000010 (CRWMS M&O 2000j)

The results of the analysis presented in *Fault Displacement Effects on Transport in the Unsaturated Zone*, ANL-NBS-HS-000020 (CRWMS M&O 2000e, Section 7) are designated by the authors as TBV. The results of this analysis are used in the support of multiple faulting- and fracture-related FEPs. The referenced AMR (CRWMS M&O 2000e) lists Assumptions 5.9 and 5.10 as TBV. These assumptions are sensitive to perched-water conceptual models. Resolution of these TBVs depends on the qualification of the flow-and-transport models used for the TSPA-SR. Based on the TBV requirements as presented in AP-3.15Q, the information from the referenced AMR (CRWMS M&O 2000e) is considered as "NA-Technical Product Output" for the purposes of this AMR. Resolution of the TBV items, however, is not expected to change the Screening Decisions discussed in Section 6.2.

Seismic (ground motion) impact analyses are provided in the *Input Request for Seismic Evaluations of Waste Packages and Emplacement Pallets* (CRWMS M&O 2000f). The input request includes the results of analyses examining the potential impact of seismicity (ground motion) on the drip shields, and on the emplacement pallets and waste packages. These results are considered preliminary, and similar analyses are designated as TBV in *FEPs Screening of Process and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 (CRWMS M&O 2000g, Section 6.2.3) and *EBS Radionuclide Transport Abstraction* ANL-WIS-PA-000001 CRWMS M&O 2000h, Section 6.5.4 and 6.5.5). Based on the TBV requirements as presented in AP-3.15Q, the information from the referenced AMRs (CRWMS 2000f, 2000g, and 2000f) is considered as "NA-Technical Product Output" for the purposes of this AMR. Resolution of the TBV items, however, is not expected to change the Screening Decisions discussed in Section 6.2.

The results presented in *Drift Degradation Analysis* ANL-EBS-MD-000027 (CRWMS M&O 2000i) and in *Supporting Rock Fall Calculation for Drift Degradation: Drift Reorientation with No Backfill* CAL-EBS-MD-000010 (CRWMS M&O 2000j) are used to support screening for the FEPs for "Rockfall (large block)" (2.1.07.01.00) and "Mechanical degradation or collapse of drift." TBVs described in *Drift Degradation Analysis* ANL-EBS-MD-000027 (CRWMS M&O 2000i) include TBV-4412 and TBV-4408. TBV-4412 is the result of using unqualified inputs regarding fracture orientation and spacing. The fracture inputs, however, are based on final, qualified fracture data, so no significant change is expected. The TBV was assigned pending verification of the inputs. TBV-4408 is the result of using unqualified vibratory ground-motion parameters in the seismic analysis; the peak ground velocity and the peak ground acceleration were preliminary subsurface-ground-motion values derived from the results of the *Preliminary Seismic Hazard Analysis for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada* (or PSHA) (USGS 1998). Based on the TBV requirements as presented in AP-3.15Q, the information from the referenced AMR (CRWMS M&O 2000i) is considered as "NA-Technical Product Output" for the purposes of this AMR. The potential impacts of changes in these values are not currently known.

All data used in the supporting calculation, *Supporting Rock Fall Calculation for Drift Degradation: Drift Reorientation with No Backfill* CAL-EBS-MD-000010 (CRWMS M&O 2000j), have been qualified. However, the rock bulk properties used in the analysis are currently considered as TBV. The rock-properties data are from qualified sources but require verification. Resolution of this TBV is not expected to significantly change the results of the calculation because the values used are based on the mean values and standard deviations of the results of geotechnical test performed on core samples from boreholes at the Yucca Mountain site. Based on the TBV requirements as presented in AP-3.15Q, the information from the referenced AMR (CRWMS M&O 2000j) is considered as "NA-Technical Product Output" for the purposes of this AMR. Resolution of the TBV items, however, is not expected to change the Screening Decisions discussed in Section 6.2.

4.2 CRITERIA

This AMR complies with criteria detailed in the DOE's Interim Guidance (Dyer 1999) and proposed rule 10 CFR 63 (64 FR 8640). The Subparts of the DOE's Interim Guidance and 64 FR 8640 that apply to this analysis are those general-information criteria requiring the characterization of the Yucca Mountain site (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); 64 FR 8640, 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); 64 FR 8640, Subpart E, Section 114(a)). Additional criteria include the NRC-specified Acceptance Criteria and the technical-screening criteria provided in Dyer (1999) and in the NRC's and EPA's proposed rules.

4.2.1 NRC Key Technical Issues and Acceptance Criteria

Analysis of individual Disruptive Events FEPs help address related KTI Subissues and Integrated Subissues from subject-specific Issue Resolution Status Reports (IRSRs). Of particular importance are the *Issue Resolution Status Report Key Technical Issues: Structural Deformation and Seismicity* (NRC 1999a) and the *Issue Resolution Status Report Key Technical Issues: Igneous Activity* (NRC 1999b). The FEPs, in many instances, do not directly address the Acceptance Criteria in the referenced IRSRs. However, the Screening Argument and TSPA Disposition statements provided in Section 6 of this AMR do cite AMRs, calculations, and other supporting information that are relevant to and that address the criteria in the cited IRSRs. The relationship of the FEPs to the Subissues and to Integrated Subissues (ISI) in the cited IRSRs is provided in Attachment II of this AMR.

The identification and screening of FEPs, however, are specifically discussed in *Issue Resolution Status Report Key Technical Issue: Total System Performance Assessment and Integration* (TSPAI)(NRC 2000) for Subissue 1: System Description and Demonstration of Multiple Barriers: Features, Events, and Processes Identification and Screening (see Section 4.2.1.1); and Subissue 2: Total System Performance Assessment Methodology: Scenario Analysis (see Section 4.2.1.2 through 4.2.1.4). The applicable Acceptance Criteria and the specific Technical Acceptance Criteria (T1, T2, etc.) from the TSPAI are identified in the following subsections.

4.2.1.1 TSPAI Subissue 1 Acceptance Criterion: Features, Events, and Processes Identification and Screening

The TSPAI (NRC 2000) states that "DOE will identify and classify those FEPs to be combined into scenarios and screen those FEPs to be excluded from further consideration. DOE's TSPA will be evaluated to determine if DOE has adequately identified and addressed those FEPs that are sufficiently likely to occur within the compliance period." The associated Technical Acceptance Criteria include:

> Criterion T1: The screening process by which FEPs were included or excluded from the TSPA is fully described.
>
> Criterion T2: Relationships between relevant FEPs are fully described.

To help satisfy Criterion T1, the FEP screening process for the Disruptive Events FEPs is described in Section 1.3 and Section 6.1 of this AMR. The relationships of the Disruptive Events Primary FEPs to other relevant FEPs are detailed in Attachment II of this document, and provide support to satisfy Criterion T2. The classification of FEPs as primary or secondary is discussed in Section 1.2 of this AMR and provides support to satisfy Criterion T2.

4.2.1.2 TSPAI Subissue 2 Acceptance Criterion: Identification of an Initial Set of Processes and Events

The TSPAI (NRC 2000) states that DOE's approach to identifying an initial list of processes and events will be acceptable if the following Technical Acceptance Criterion is met:

> Criterion T1: DOE has identified a comprehensive list of processes and events that (i) are present or might occur in the YM region (YMR) and (ii) includes those processes and events that have the potential to influence repository performance.

To help satisfy Criterion T1, a summary of the approach and methods used to identify the list of processes and events is provided in Section 1.2 of this AMR. An extensive discussion regarding the approach and identification of the list of processes and events is provided in *The Development of Information Catalogued in REV 00 of the YMP FEP Database* TDR-WIS-MD-000003 REV 00 (CRWMS M&O 2000c).

4.2.1.3 TSPAI Subissue 2 Acceptance Criterion: Classification of Processes and Events

The TSPAI (NRC 2000) states that DOE's classification of processes and events will be acceptable, if the following Technical Acceptance Criteria are met:

> Criterion T1: DOE has provided adequate documentation identifying how its initial list of processes and events has been grouped into categories.
>
> Criterion T2: Categorization of processes and events is compatible with the use of categories during the screening of processes and events.

To help satisfy Criterion T1 and T2, the categorization (or classification) of the list of processes and events is discussed in Section 1.2 of this AMR. The categorization is also addressed through the database organization and FEP numbering as summarized in Section 1.4 of this AMR. Details regarding the categorization are provided in *The Development of Information Catalogued in REV 00 of the YMP FEP Database* TDR-WIS-MD-000003 REV 00 (CRWMS M&O 2000c).

4.2.1.4 TSPAI Subissue 2 Acceptance Criterion: Screening of Processes and Events

The TSPAI (NRC 2000) states that DOE's screening of categories of processes and events will be acceptable if the following Technical Acceptance Criteria are met:

> Criterion T1: Categories of processes and events that are not credible for the YM repository because of waste characteristics, repository design, or site characteristics are identified and sufficient justification is provided for DOE's conclusions.

Criterion T2: The probability assigned to each category of processes and events *[. . .]* is consistent with site information, well documented, and appropriately considers uncertainty. *[Note: The omitted language in Criterion T2, as noted by the brackets [. . .], is "not screened based on Criterion T1 or T2." However, the TSPAI does not clarify which Criterion T1 and T2 are being referenced, so it has been omitted here for clarity.]*

Criterion T3: DOE has demonstrated that processes and events screened from the PA on the basis of their probability of occurrence, have a probability of less than one chance in 10,000 of occurring in 10,000 years.

Criterion T4: DOE has demonstrated that categories of processes and events omitted from the PA on the basis that their omission would not significantly change the calculated expected dose, do not significantly change the calculated expected annual dose.

To help satisfy Criteria T1, T3, and T4, the Screening Decision (either *Included* or *Excluded*) and the Regulatory Basis (which is expressed as "low probability" or "low consequence to dose") are listed for each Disruptive Events Primary FEP in Section 6.2 of this AMR. The technical bases for the decision is provided in the Screening Argument and/or TSPA Disposition discussions. Similar information for the related Secondary FEPs is provided in Attachment II of this AMR.

Criterion T1 allows for screening based on repository design and corresponds to Assumptions 5.2 and 5.3 discussed in Section 5.0 of this AMR. Accordingly, Criterion T1 is, at least partially, satisfied because where "not credible" arguments are used, the potential magnitude of a process or event is contrasted to and shown to be addressed by a specific repository-design element. The sources of information for both the magnitude of the event and for the design element are cited.

Criterion T2 is concerned with the basis used to determine probability for FEPs that are to be included in the TSPA. Criterion T2 is, at least, partially satisfied because the probabilities used in the Disruptive Events FEP screening and in the TSPA-SR are based on the results of expert elicitation, which are consistent with site data, well-documented, and consider uncertainty. In particular, the expert-elicitation process was used to develop probabilities for seismicity and fault displacement and the results are presented in the PSHA (USGS 1998). The probabilities of fault displacements at various representative reference points for the repository (see the subheading Fault Displacement Evaluation in Section 6.2.3 for Point descriptions) are cited as the basis for excluding the formation of new fractures and new faults, and are also used to determine whether fault displacements would affect the repository such that the displacements would significantly change the calculated expected annual dose (see Section 6.2.2 and 6.2.3). The expert-elicitation process was also used for evaluating the probability of igneous activity. The results of the igneous-activity expert elicitation are not cited directly but are used in development of the AMRs cited for the igneous-related FEPs and for the TSPA-SR calculations.

Criteria T3 and T4 are, at least partially, satisfied by the discussions provided in Sections 1.3.2 and 1.3.3, which specifically address the application of "low probability" and "low consequence to dose" to FEP screening. As described in Section 1.3.2, low probability is considered on two bases: (1) the probability of a geologic event (e.g., seismicity and faulting), and (2) the probability of a specific behavior of the repository in response to a geologic process. The low-consequence-to-dose argument, as described in Section 1.3.3, is used if it is demonstrated that there is no effect on the distribution of an intermediate performance measure in the TSPA. FEP-specific application of "low probability" and "low consequence to dose" are provided for each Disruptive Events FEP in Section 6.2.

4.2.2 FEP Screening Criteria

DOE's technical screening criteria are provided in DOE's Interim Guidance (Dyer 1999). These FEP-screening criteria are also identified by the NRC in proposed rule 10 CFR Part 63 (64 FR 8640). Additional screening criteria are identified by the EPA in 40 CFR Part 197 (64 FR 46976). The DOE's Interim Guidance and the proposed NRC 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 ($10^{-4}/10^{4}$ yr) or, as explained in Assumption 5.4, an equivalence of 10^{-8} annual-exceedance probability), or if occurrence of the FEP can be shown to have negligible effect on expected annual dose. These technical screening criteria are the same as those discussed in Section 4.2.1.4 for Criteria T1 and T3. Other criteria are specified in the assumptions, guidance, or proposed regulations that address the reference biosphere and the critical group.

The following subsections provide the regulatory citations for the technical screening criteria used for the FEP-screening process. The criterion for "low probability" is discussed in Section 4.2.2.1 and for "low consequence to dose" is described in Section 4.2.2.2. The criteria for "low probability" and "low consequence to dose" are used as the basis for all of the FEP screenings. Information regarding the reference biosphere (Section 4.2.2.3) and the critical group (Section 4.2.2.4) establishes other pertinent factors that must be considered during the FEP screening. These other factors include consideration of future states of the geologic setting and the distance from the repository to the potential receptors.

4.2.2.1 "Low Probability"

The low-probability criterion is explicitly stated in the DOE's Interim Guidance (Dyer 1999, Section 114(d)), and proposed rule 10 CFR 63 (64 FR 8640, 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 rule 40 CFR §197.40 (64 FR 46976):

> 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.

The low-probability criterion is stated as less than one chance in 10,000 of occurring in 10,000 years ($10^{-4}/10^{4}$ yr, or as explained in Assumption 5.4, an equivalence of 10^{-8} annual-exceedance probability). The use of low-probability criterion for FEP Screening is described in Section 1.3.2 of this AMR. As described in Section 1.3.2, "low probability" is considered on two bases: (1) the probability of a geologic phenomenon (e.g., faulting), and (2) the probability of a specific behavior of the repository in response to a geologic process (e.g., fault movement shears waste container).

The low-probability criterion is used for the Disruptive Events FEPs screening in association with the results of expert elicitation. The expert-elicitation process was used to develop probabilities for seismicity and fault displacement and the results are presented in the PSHA (USGS 1998). The probabilities of fault displacements at various representative reference points for the repository (see the subheading Fault Displacement Evaluation in Section 6.2.3 for Point descriptions) are cited as the basis for excluding the formation of new fractures and new faults, and are also used to determine whether fault displacements would affect the repository such that dose would be significantly changed (see Sections 6.2.2, 6.2.3, and 6.2.4).

The PSHA (USGS 1998) is of particular interest because at low annual-exceedance probabilities (10^{-6} to 10^{-8} annual- exceedance probabilities), the magnitude of the calculated ground motion and fault displacement is driven by the tail of the uncertainty distribution. The integrated summary hazard curve for fault displacement based on the Solitario Canyon fault (USGS 1998, Figure 8-3), suggests that the fault displacement at a 10^{-8} annual-exceedance probability could range from 1 m to 5 m or greater. The median fault displacement on the Solitario Canyon at a 10^{-8} annual-exceedance probability is 3 m. However, physical observations of displacements from trenches excavated at the Yucca Mountain site and studies in the Exploratory Studies Facility (ESF) indicate that the maximum per-event displacement over the last 250 k.y. is no larger than 1.3 m (Ramelli et al. 1996, p. Table 4.7.3). A displacement of 1.3 m falls within the lower fractiles of the uncertainty range for the 10^{-8} annual-exceedance probability and below the median values provided in PSHA (USGS 1998).

Dyer (1999, Section 114(l)) provides direction and is echoed by the NRC at proposed rule 10 CFR 63.115(a)(4), stating that the performance assessment should:

> . . . assume evolution of the geologic setting consistent with present knowledge of natural processes.

Similarly, the EPA has specified that the DOE must consider the changes that could occur in the next 10,000 years at proposed rule 40 CFR §197.15 (64 FR 46976). This assumption is stated 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.

The FEP-screening discussions cite the range of values presented in the PSHA (USGS 1998), and postclosure FEPs screening is performed against the median value. The median value, rather than the mean value, is used for postclosure FEPs screening because it is a better representation of the central tendency of the hazard at low annual-exceedance probabilities; it is more consistent with observed fault displacements; and it is a reasonable scientific prediction as required by the EPA. The basis for using the median value is further justified in Assumption 5.5 (see Section 5.0).

4.2.2.2 "Low Consequence to Dose"

Criteria for low-consequence-to-dose screening arguments are provided in DOE's Interim Guidance (Dyer 1999, 114(e) and (f)), and NRC's proposed rule 10 CFR 63 (64 FR 8640, Section 114(e) and (f)), which indicate 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 at proposed rule 40 CFR §197.40 (64 FR 46976):

> . . . 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 NRC's and in the EPA's proposed regulations. These terms are inferred for FEP-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."

The use of low-consequence-to-dose arguments for FEP screening is described in Section 1.3.3 of this AMR. Low consequence to dose, as described in Section 1.3.3, is used if it is demonstrated that there is no effect on the distribution of an intermediate performance measure in the TSPA.

4.2.2.3 Reference Biosphere and Geologic Setting

DOE's Interim Guidance and the NRC's and EPA's proposed regulations specify assumptions (which in effect serve as FEP-screening criteria) pertinent to screening many of the Disruptive Events FEPs. Particularly germane are explicit assumptions regarding the reference biosphere and the geologic setting.

An assumption pertaining to the characteristics of the reference biosphere is presented in DOE's Interim Guidance (Dyer 1999, Section 115 (a)(1)) and in proposed rule 10 CFR 63 (64 FR 8640, Section 115 (a)(1).

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

With regard to changes in the geologic setting, Dyer (1999, Section 114(l)) and the NRC at proposed rule 10 CFR 63 (64 FR 8640, Section 115(a)(4)) state that:

> Evolution of the geologic setting shall be consistent with present knowledge of natural processes.

The EPA has specified a similar assumption regarding changes that will occur in the next 10,000 years in proposed rule 40 CFR §197.15 (64 FR). 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 require that present knowledge of the geologic and hydrologic system be considered in the performance assessment. Consequently, existing features such as faults and fracture systems have been included in the geologic framework and UZ and SZ flow models, and various rock properties and behaviors of igneous events have been included in the models and analysis used as a basis for FEPs screening. As a result, FEPs Screening Decisions may indicate that existing features are *Included* in the TSPA-SR, while changes to features may be *Excluded* from the TSPA-SR based on "low probability" or "low consequence to dose."

These criteria also specify the duration of the regulatory period of concern (10,000 years). In contrast to geologic processes, this duration is relatively short. Consequently, some geologic process may be excluded based on "low probability" or "low consequence to dose" because the regulatory period of concern is shorter than the time period (100,000 years or greater) needed for geologic processes to result in effects that would significantly affect dose.

4.2.2.4 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)) and at proposed rule 10 CFR 63 (64 FR 8640, Section 115(b)). Pertinent to the Disruptive Events FEPs is 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); 64 FR 8640, Section 115(b)(1))

The EPA-specified assumptions are provided at proposed rule 40 CFR §197.21(a-c) (64 FR 46976) 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 from the repository 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 at proposed rule 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.

The distance from the repository is of primary interest in evaluating results of igneous-related transport FEPs. For example, generally speaking, the potential magmatic transport mechanism at Yucca Mountain would occur over distances significantly less than 20 km. This allows for the FEP to be *Excluded* from the TSPA-SR based on "low consequence to dose" because the radionuclides could potentially be transported by magma only a small fraction of the distance toward the critical group. The potential increases in radionuclide source terms from deposition of ash also take into account the distance from repository to the critical group.

4.3 CODES AND STANDARDS

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

5. ASSUMPTIONS

There are five general assumptions used in screening of the Disruptive Events FEPs for the TSPA-SR.

Assumption 5.1: For the Disruptive Events FEP-screening analyses, there is an assumption that the tectonic strain rates at Yucca Mountain will not vary significantly on a local or regional scale through the repository-performance period (10,000 years). Additionally, it is assumed that existing knowledge of natural processes is sufficient to adequately characterize future states of the geologic system.

> Justification: This assumption is justified because it is consistent with the existing guidance and screening criteria pertaining to present knowledge of natural processes. As directed by Dyer (1999, Section 114(l)) and the proposed rule 10 CFR 63 (64 FR 8640, Section 115(a)(4)), the TSPA also assumes that the evolution of the geologic setting is consistent with present knowledge of natural processes.
>
> At Yucca Mountain, increased rates of tectonic activity and igneous activity in the geologic past were associated with greater crustal-strain rates than exist in the present. A geologic condition that would reduce rates or number of incidences for tectonic activity would favorably impact the potential for containment by the repository. As discussed in the context of specific FEPs in Section 6, available information indicates that crustal-extension rates are likely to vary insignificantly or to decrease throughout the performance period. The rate of subsidence appears to have 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). The assumption that crustal-strain rates will not vary significantly from the present rates is, therefore, conservative because it allows for greater than expected tectonic activity. Consequently, there is conservatism in the exclusion of the FEP "Tectonic activity–large scale" because the small magnitude and rate of change are overstated, and the probability of igneous activity, although *Included* in the TSPA-SR, is also conservatively overstated. Because the assumption is reasonable and conservative, it requires no further confirmation.

Use: This assumption is particularly germane to Disruptive Events FEPs because the FEPs are concerned with geologic processes (e.g., tectonic, seismic, and igneous processes) that are influenced by crustal-strain rates. This assumption is used specifically for the FEP "Tectonic activity–large scale" (1.2.01.01.00) (Section 6.2.1), and "Fractures" (1.2.02.01.00) (Section 6.2.2), but it is also applicable (though not specifically used in the screening arguments) to other FEPs related to changes in stress and strain caused by geologic processes.

Assumption 5.2: Design parameters can be used to justify an "*Excluded* from the TSPA-SR" FEP-screening decision, if the design parameter eliminates or alleviates the FEP (i.e., in some cases the screening decision is design-dependent). Design parameters can be used to support both low- probability and/or low-consequence-to-dose arguments.

Justification: For the TSPA, the YMP defines an event as "a natural or anthropogenic phenomenon that has a potential to affect repository 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 and some component of the repository system, which potentially leads to significantly changed performance. The design parameters determine, to some extent, the nature of the interaction of the geologic process with the waste packages or other designed features. If a design parameter is instituted which eliminates or alleviates the interaction, then the FEP Screening Decision can be determined on that basis.

For example, the repository design includes installation of drip shields. The FEP "Rockfall (large block)" is excluded based on the performance characteristics of the drip-shield design. Because the largest calculated rockfall does not breach the drip shield, the waste packages remain unaffected. As a result, the FEP "Rockfall (large block) could be excluded as either a "non-credible" event (or "low probability"), or it could be excluded based on "low consequence to dose" because "Rockfall (large block)" does not provide a mechanism to damage the waste package and, thereby, increase the dose.

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 in such a way that the potential effect of the FEP is eliminated or minimized; (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). Additionally, the TSPAI (NRC 2000, Subissue 2 Acceptance Criterion: Screening of Processes and Events, Criterion; see Section 4.2.1.3 of this AMR) allows for screening based on repository design. Because of the justifications in provided in Items 2,3, and 4 above, the assumption is reasonable, and because the Acceptance Criterion allows this assumption, no further confirmation is needed.

Use: This assumption is particularly germane to FEPs involving potential breaching of containers due to some geologic phenomenon, such as "Fault movement shears waste container" (1.2.02.03.00) (Section 6.2.4), and the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (Section 6.2.6). The FEP "Fault movement shears waste container" 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 also relevant to the FEP "Seismic vibration causes container failure" (1.2.03.02.00), because the design determines the potential for damage from ground motion. This assumption is also used in support of excluding the FEPs "Rockfall (large block) (2.1.07.01.00)(Section 6.2.17) and "Mechanical degradation or collapse of drift" (2.1.07.02.00) (Section 6.2.18)

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.

Justification: This assumption is justified because when a design change occurs, the potential for impact on FEP-screening decisions is evaluated. Changes in the design require a reevaluation of the screening decision for FEPs that are dependent on design requirements. This assumption is also justified based on the conditions specified by 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. Furthermore, the TSPAI (NRC 2000, Subissue 2 Acceptance Criterion: Screening of Processes and Events, Criterion T1 ; see Section 4.2.1.3 of this AMR) allows for screening based on repository design.

For example, this AMR was originally issued (REV 00) based on consideration of a repository design with backfill, based on *License Application Design Selection Report* (LADs) (CRWMS M&O 1999a, EDA II, p. 0.21 to 0.26 and Section 7). On January 26, 2000 a design change was initiated to resolve certain thermal design issues. This design change was described in Technical Change Request T2000-0133, dated January 26, 2000 (CRWMS M&O 2000a). Additional design changes have been noted in "Repository Subsurface Design Information to Support TSPA-SR" PA_SSR-99218.Tc (CRWMS M&O 2000b). The design considerations included reorienting the emplacement drifts to azimuth 252/72, including a drip shield, removing the backfill from the design, and evaluating a repository layout and relocation northward to accommodate both a 70,000-MTU and 97,000-MTU design. The design changes have been evaluated for the FEP screening decisions presented in this AMR. This is an inherent assumption for engineering projects, and design/construct is required as part of the construction process. No further confirmation is required.

Use: Unless a FEP is excluded because of a low probability of the phenomenon occurring, the FEP screening decision is based, at least in part, on the design used for the comparison. For example, the repository design includes installation of drip shields. The FEP "Rockfall (large block)" is excluded based on the performance characteristics of the drip-shield design. If the drip shield were to be deleted from the design, or constructed differently from the design used for the analysis, the FEP would need to be reevaluated.

This assumption is particularly germane to FEPs involving potential breaching of containers such as "Fault movement shears waste container" (1.2.02.03.00) (Section 6.2.4) and "Seismic vibration causes container failure" (1.2.03.02.00) (Section 6.2.6). The presence of the drip shield (a design feature) limits the potential for rockfall or drift degradation to breach the containers (see discussion for the FEPs "Rockfall (large block)" (2.1.07.01.00) (Section 6.2.17) and "Mechanical degradation or collapse of drifts" (2.1.07.02.00) (Section 6.2.18)).

Assumption 5.4: For postclosure seismic-related and fault-related FEPs, it is assumed that the probability criterion of one chance in 10,000 in 10,000 years ($10^{-4}/10^{4}$ yr) is equivalent to a 10^{-8} annual-exceedance probability.

Justification: This approach is justified based on the definition of an event as "a natural or anthropogenic phenomenon that has a potential to affect repository performance and that occurs during an interval that is short compared to the period of performance." The assumption of equivalence of $10^{-4}/10^{4}$ yr to the 10^{-8} annual-exceedance probability is justified if the possibility of an event is equal for any given year. For geologic processes that occur over long time spans, assuming annual equivalence over a 10,000-year period (a relatively short time span) for geologic-related events is reasonable. Therefore, no further confirmation is required.

Use: This assumption is used for the FEP "Fractures" (1.2.02.01.00) (Section 6.2.2); the fault-related FEPs "Faulting" (1.2.02.02.00) (Section 6.2.3) and "Fault movement shears waste container" (1.2.02.03.00); and the seismic-related FEP "Seismic vibration causes container failure." (1.2.03.02.00) (Section 6.2.6). This assumption is also used for the FEP "Rockfall (large block)" (2.1.07.01.00) (Section 6.2.17) and the FEP "Mechanical degradation or collapse of drift" (2.1.07.02.00)(Section 6.2.18). This assumption is also used for the FEPs "Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock " (2.206.01.00) (Section 6.2.19) and "Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults" (2.2.06.02.00).

Assumption 5.5: For postclosure evaluation of fault- and seismic-related (ground motion) FEPs, the postclosure fault-displacement and ground-motion hazards are better represented by the median value, rather than the mean value or 85^{th} fractile value, due to large uncertainties associated with 10^{-6} to 10^{-8} annual-exceedance probabilities. The median value is representative for postclosure analyses and FEPs-screening.

Justification: The use of the median fault displacement and median ground-motion values for postclosure evaluations (10^{-5} to 10^{-8} annual-exceedance probabilities) are justified because they better expresses the central tendencies of the hazards and are less influenced by the tails of the uncertainty distributions. Additionally, as discussed in Section 4.2.2.1, the use of the median value best satisfies the regulatory intent to "assume evolution of the geologic setting consistent with present knowledge of natural processes."

Epistemic uncertainty in the hazard results is highly skewed and the degree of skewness increases with decreasing annual probability. At annual-exceedance probabilities below 10^{-5} to 10^{-6}, such as the range between 10^{-5} and 10^{-8} used for postclosure fault-displacement evaluations, the mean fault-displacement hazard curve approaches the 85th fractile, then crosses it. At 10^{-8} annual-exceedance probabilities, the mean displacement coincides with the 99th fractile (USGS 1998, Figures 8.2 to 8.13). For fault displacements, this indicates that the mean displacement is being determined at these very low probabilities by the tails of the uncertainty distributions, which are modeled in the PSHA, in accordance with current practice, as lognormal and unbounded (USGS 1998). These values do reflect the current state of scientific and modeling uncertainty, but in considering the hazard results, the fault displacements associated with 10^{-6} and lower annual-exceedance probabilities are increasingly too large when compared to the observed, maximum fault displacements along the Solitario Canyon and the Bow Ridge faults

For the Solitario Canyon, the cross-over of the mean and the 85th fractile occurs at the 10^{-7} annual-exceedance probability and corresponds to a displacement of approximately 5 m (USGS 1998, Figure 8.3). The median fault displacement for the Solitario Canyon at the 10^{-8} annual-exceedance probability is 3 m, and the maximum observed displacement along the Solitario Canyon fault for a single-event movement is 1.3 m (Ramelli et al. 1996, p. 4.7-44, Table 4.7.3), or slightly above the 15th fractile for the 10^{-8} annual-exceedance probability. For the Bow Ridge fault, the cross-over of the mean and the 85th fractile occurs at a slightly greater than a 10^{-7} annual-exceedance probability and corresponds to a fault displacement of about 2 m (USGS 1998, Figure 8.2). However, the median fault displacement for the 10^{-8} annual-exceedance probability is 2 m, and the maximum single-event displacement is reported as a preferred value of 0.44 m, with a maximum of 0.8 m (Whitney et al. 1996, Table 4.4-3), or at about the 15th fractile for the 10^{-8} annual-exceedance probability. The maximum observed value also falls between the mean and median fault displacements for the 10^{-6} annual-exceedance probabilities.

Because of the highly skewed distribution, the median hazard is considered a more appropriate representation of the central tendency for purposes of FEPs screening for postclosure performance evaluation. Moreover, the median-hazard results are more consistent with fault displacements at Yucca Mountain over the past several hundred thousand years, as obtained from detailed investigations of fault and faulting for the YMP.

Although the effects of the upper tails of the uncertainty distributions are not as significant for ground-motion hazard as they are for fault-displacement hazard, they nevertheless dominate the hazard at low annual probabilities. As suggested in the PSHA (USGS 1998, Figures 7-15 and 7-16), at 10^{-4} annual-exceedance probability, the hazard is dominantly from ground motion that is more than one standard deviation above the mean, and a significant contribution comes from ground motion that is more than two standard deviations above the mean. Based on the seismic hazard summary curves presented in the PSHA (USGS 1998, Figures 7-4 through 7-13), it seems reasonable to anticipate that, at annual-exceedance probabilities in the range of 10^{-6} to 10^{-8}, the ground-motion hazard is also increasingly dominated by ground motion that is more than two standard deviations above the mean. This behavior suggests that, at low annual-exceedance probabilities, the ground-motion hazards are dominantly from the upper tails of the experts' uncertainty distributions on seismic sources, earthquake recurrence, and maximum magnitude.

In summary, uncertainty in the input parameters for ground-motion and fault-displacement hazard evaluations, following standard practice, has been modeled assuming an unbounded lognormal distribution for the Yucca Mountain PSHA (USGS 1998), a first-of-a-kind assessment of hazard for annual-exceedance probabilities as low as 10^{-8}. Use of the lognormal distribution is considered conservative and largely explains the highly skewed distribution of hazard results at low annual-exceedance probabilities. In any case, the consequence of the lognormal distribution is that the mean hazard increasingly diverges from the median such that, at annual-exceedance probabilities in the range of 10^{-6} and lower, the mean may become larger than the 95th fractile of the uncertainty distribution. Consequently, the median hazard curve, rather than the mean or 85th fractile curve, is statistically more stable; therefore, it is a better measure of the central tendency of the hazard results at low annual probabilities. No further confirmation of this assumption is needed.

Use: This assumption is used for the fault-related FEP "Fault movement shears waste container" (1.2.02.03.00) (Section 6.2.4) and the seismic-related FEP "Seismic vibration causes container failure" (1.2.03.02.00) (Section 6.2.6). This assumption is also used to for the FEPs "Rockfall (large block)" (2.1.07.01.00) (Section 6.2.17) and "Mechanical degradation or collapse of drift" (2.1.07.02.00) (Section 6.2.18). This assumption is also used for the FEP "Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock" (2.206.01.00) (Section 6.2.19) and "Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults" (2.2.06.02.00) (Section 6.2.20).

6. ANALYSES

This Section documents the Screening Decision and Regulatory Basis, Screening Argument, and TSPA Disposition for each of the 21 Disruptive Event Primary FEPs. The following paragraphs discuss the appropriateness and importance of these analyses. Section 6.1 discusses alternative approaches to the FEPs screening, and Section 6.2 provides the documentation for the individual Primary FEPs.

The FEP analyses presented in Section 6.2 are appropriate because, as described in Section 1, they are consistent with the TSPA approach to satisfy the performance-assessment requirements. 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 (Section 1.3), and analysis to determine a Screening Decision of either *Included* in the TSPA-SR or *Excluded* from the TSPA-SR (see Section 6.2 and individual FEP subsections). These analyses satisfy the second step for the Disruptive Events FEPs.

These analyses are also appropriate because they address NRC's Acceptance Criteria (presented in Section 4.2.1), which are applicable to all of the FEPs discussions provided in Section 6.2. The identification of the list of processes and events is provided in Section 1.2 of this AMR. Additional detail regarding identification is provided in the CRWMS M&O (2000c). The relationships between Primary FEPs are detailed in Attachment II of this document. The classification of FEPs as primary or secondary is discussed in Section 1.2 of this document, and the relationship of primary and secondary FEPs is provided in Attachment II for each of the Primary FEPs. The FEP-screening process is described in Section 1.3 of this AMR. In Section 6.2 and the individual FEP subsections, the Screening Decision and Regulatory Basis, the Screening Argument, and the TSPA Disposition are discussed for each Disruptive Event Primary FEP. Similar information for the related Secondary FEPs is provided in Attachment II of this AMR. Where low-probability arguments are used, the basis for "low probability" is stated and a reference is cited. Where a low-consequence-to-dose argument is used, the basis for exclusion on "low consequence to dose" is also provided. These items are all listed in the NRC's Acceptance Criteria

These analyses are also appropriate because the screening criteria used for the analyses are based on the assumptions, guidance, and specific criteria provided in Dyer 1999, and those proposed by the NRC at proposed rule 10 CFR Part 63 (64 FR 8640) and by the EPA in proposed rule 40 CFR Part 197 (64 FR 46976). The criteria are used to determine whether or not a FEP should be excluded from the TSPA.

- For FEPs that are *Excluded* from the TSPA-SR 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 Disruptive Events Primary FEPs are *Excluded* from the TSPA-SR based solely on proposed regulatory requirements or regulatory-specified assumptions.

- For FEPs that are *Excluded* from the TSPA-SR based on the screening criteria from DOE's Interim Guidance (Dyer, 1999) or based on the screening criteria from NRC's or EPA's proposed regulations, the Screening Argument includes the regulatory basis of the exclusion ("low probability" (Section 4.2.1), or "low consequence to dose" (Section 4.2.2)) and provides the technical argument for exclusion. As appropriate, Screening Arguments cite work done outside this activity, such as in other AMRs or from expert elicitations.

- For FEPs that are *Included* in the TSPA-SR, 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-SR.

Based on the determination of importance presented in AP-3.10Q (Attachment 6, Item 6), and as directed by AP-3.10Q, based on the "Screening Criteria For Grading of Data" (AP-3.15Q, Attachment 6), this FEP-screening analysis is of Level 3 importance. The "Screening Criteria For Grading of Data" indicates, under the heading of "Potentially Disruptive Processes and

Events," that this "does not include data used to screen features, events, and processes from further consideration in postclosure performance assessments." Consequently, Level 3 is assigned because the FEPs analyses do not provide estimates of any of the Factors or Potentially Disruptive Events listed in the "Screening Criteria For Grading of Data."

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 for inclusion or exclusion (see Sections 1.2 and 1.3).

The approach described in Section 1.2 and 1.3 is also used to identify, analyze, and screen FEPs. 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. Alternative classifications of the FEPs are entirely possible but would still be based on subjective judgement. Subsequent to classification, the FEPs were assigned to the PMRs for evaluation by knowledgeable subject-matter experts (see Section 1.1). This appeared to be the most efficient methodology for ensuring a comprehensive assessment of FEPs as they relate to the TSPA.

Alternative approaches for determining probabilities and consequence-to-dose values used as a basis for screening are discussed in Section 6.2 under the individual FEP analyses and in the referenced AMRs. In practice, regulatory-type criteria are examined first, and then either probabilities or consequences are examined. FEPs that are retained on one criterion are 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 low-probability arguments for "low consequence to dose" events or complex, low-consequence-to-dose 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 is shown that fault-shearing events have a probability below the threshold of the screening criteria.

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 FEP screening are provided in the Screening Argument, TSPA Disposition, or Supplemental Discussion section for each FEP, as discussed below. The FEP-screening decisions may also rely on the results of analyses performed and documented as separate activities. Alternative 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 FEPs that are identified as Disruptive Events Primary FEPs. These FEPs represent areas of natural-system processes that have the potential to produce disruptive events that could impact repository performance. The FEPs are related to the geologic processes of tectonism, structural deformation, seismicity, and igneous activity. Of these 21 Primary FEPs, 16 are addressed explicitly and fully in this AMR.

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

Attachment II of this AMR provides the relationship of the Primary FEPs to IRSR Subissues, to ISIs, and to other related Primary FEPs being addressed in other FEP AMRs. The relationship of the Primary FEP to the associated Secondary FEPs is also detailed in Attachment II.

The Secondary FEPs are listed in Table 4 (Section 7) and in Attachment II. Secondary FEP descriptions are available from the YMP FEP Database (CRWMS M&O 2000c, Appendix D), and they are provided in Attachment II. All Secondary FEPs have been evaluated and are incorporated into the encompassing Primary FEP descriptions. Consequently, dispositions of the Primary FEPs provided below are sufficient to address Secondary FEPs.

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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose.

Potential Consequence: Tectonic activity is an on-going process in the Yucca Mountain region that has the potential to result in alteration of the physical and the thermo-hydrologic properties of the geosphere. These changes, if they occur at a sufficient rate, could potentially impact UZ and SZ flow-and-transport properties during the repository-performance period (10,000 years), thereby affecting dose. These changes could also alter the groundwater flux through the repository and the amount of water contacting elements of the EBS or the waste packages and, thereby, alter the waste form and/or performance characteristics of these elements, leading to premature failure and release of radionuclides, thereby affecting dose. Other processes related to tectonic activity (volcanism, faulting, seismicity, and fracturing) are evaluated as separate Primary FEPs.

Screening Argument: Global- or plate-scale tectonics, ultimately, drive the tectonism at the regional scale. Large-scale tectonic activity is interpreted for this

FEP to refer to tectonism that is expressed at a regional scale (1:250,000 or less) and has the potential for broad uplift, subsidence, folding, and geothermal effects. However, tectonic activity will not result in significant localized changes at Yucca Mountain during the repository-performance period (10,000 years) due to the slow rate at which tectonic processes proceed, the distance to the margins of the continental plate that includes Yucca Mountain, and, for geothermal effects, the great depth (about 60 km) to centers of basaltic-magma generation.

The regional tectonic processes that are occurring in the Yucca Mountain region proceed at an almost imperceptible rate. The very slow, contemporary strain-accumulation rate in the Yucca Mountain area (<2 mm/yr) (Savage et al. 1999, p. 17627) has resulted in the paleoseismic slip rates calculated from fault-displacement studies. These local slip rates are in the range of 0.001–0.03 mm/yr (CRWMS M&O 2000k, Table 6). Savage et al. (1999) present an evaluation of the rate of strain accumulation at Yucca Mountain, Nevada, for the period from 1983 to 1998, and address alternative interpretations indicating higher strain-accumulation rates presented by Wernicke et al. (1998). The tectonic strain rate is evaluated as an uncertain parameter in the PSHA (USGS 1998), and the uncertainty in the rate is reflected in the PSHA fault-displacement and ground-motion hazard curves.

The present extensional-tectonic regime of the Yucca Mountain region (see Assumption 5.1 of this AMR (ANL-WIS-MD-000005)) does not promote significant tectonic uplift and mountain building. Because Yucca Mountain is in a presently waning extensional regime, any uplift of significance to a repository at Yucca Mountain could not develop within the next few million years. Because significant uplift does not occur during the repository-performance period (10,000 years), uplift does not provide a mechanism for affecting groundwater flow; therefore, uplift will not affect dose. Accordingly, uplift is *Excluded* from the TSPA-SR based on low consequence to dose.

Based on the history of the Crater Flat Basin as presented by Fridrich (1999), tectonic subsidence due to regional extension is a more likely scenario at Yucca Mountain than uplift. However, the rate of subsidence appears to have diminished consistently over the last several million years, and the locus of subsidence due to the waning 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 will be minimal. Because subsidence will be minimal during the repository-performance period (10,000 years), subsidence does not provide a mechanism that significantly affects groundwater flow; therefore, subsidence will not affect dose. Accordingly, subsidence is *Excluded* from the TSPA-SR based on low consequence to dose during the period of interest (see Assumption 5.1 of this AMR (ANL-WIS-MD-000005)).

Regional compressive stresses that could produce uplift or subsidence related to subhorizontal (compressive) fold axes have not operated in the Yucca Mountain region or in the entire Great Basin within the past 50 million years (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 (10,000 years) is negligible under the current tectonic regime. However, some minimal hanging-wall rollover folding may occur, as described later in this section. Because only minimal folding occurs during the repository-performance period (10,000 years), folding does not provide a mechanism that significantly affects groundwater flow; therefore, folding will not affect dose. Folding is, therefore, *Excluded* from the TSPA-SR based on low consequence to dose (see Assumption 5.1 of this AMR (ANL-WIS-MD-000005)).

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 is *Excluded* from the TSPA-SR based on low consequence to dose. A change in orientation of the tuff beds would most likely occur in the near vicinity of faults and be expressed as hanging-wall rollover (for further discussion, see below in this section: *Supplemental Discussion,* Folding). Given the low normal-fault activity at Yucca Mountain and the small (less than 1.3 m maximum along the Solitario Canyon) observed offsets per slip event, any increase in hanging-wall rollover large enough to affect percolation flux through the tuff beds is extremely unlikely. It is more likely that fracture permeability associated with the rollover will have a much greater influence on local flux rates than strata-confined matrix permeability that depends on the folding rate. However, changes in fracture aperture confined to fault zones show virtually no effect on transport behavior, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration (*Fault Displacement Effects on Transport in the Unsaturated Zone*, ANL-NBS-HS-000020: CRWMS M&O 2000e, Section 7).

Given the rapidity of stream-grade adjustment to climate change, percolation flux associated with changes in drainage patterns is not likely to be significantly influenced by the very slow expected rates of tectonic slope change or local base-level subsidence, within the performance period (10,000 years). Additionally, work performed for the TSPA indicates that percolation flux is strongly dependent on rainfall (*Unsaturated Zone Flow and Transport Model Process Report* TDR-NBS-HS-000002 CRWMS M&O 2000l, Section 3.5), 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 (10,000 years), 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 *Excluded* from the TSPA-SR based on low consequence to dose.

Concerns that tectonic changes could induce local geothermal flux or convective flow in the saturated zone are also *Excluded* from the TSPA-SR based on low consequence to dose. 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, Figure 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, *Excluded* from the TSPA-SR based on low consequence to dose.

Deformational processes associated with tectonism, however, can be punctuated by local events, such as earthquakes and volcanic eruptions, which are considered as potentially disruptive events, and they are treated as separate and distinct FEPs in the following sections. Igneous events are specifically addressed in *Igneous Consequence Modeling for the TSPA-SR,* ANL-WIS-MD-000017 (CRWMS M&O 2000m), and *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada,* ANL-MGR-GS-000001 (CRWMS M&O 2000n). Earthquake related events (due to ground motion and fault displacement) are specifically addressed in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada,* ANL-CRW-GS-000003 (CRWMS M&O, 2000k).

In summary, because the tectonic-strain-accumulation rate and fault-movement rates are very low; the resulting magnitude and rates of tectonically related-deformation are insignificant with respect to the repository-performance period (10,000 years). These low-rate, small-magnitude changes will not directly affect waste-package integrity or other components of the engineered barrier via the processes described in the Primary FEP description and will negligibly affect flow-and-transport properties. Consequently, tectonic-related deformations do not provide a mechanism to significantly affect dose. Tectonic activity is, therefore, considered to be *Excluded* from the TSPA-SR based on low consequence to dose. Other local processes related to tectonic activity, such as volcanism, faulting, seismicity, and fracturing, are evaluated as separate Primary FEPs.

TSPA Disposition: "Tectonic activity—large scale" and the associated Secondary FEPs are *Excluded* from the TSPA-SR, as described under the Screening Argument.

IRSR Issues / Related FEPs: See Attachment II

Related AMRs: *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* ANL-CRW-GS-000003 (CRWMS M&O 2000k)

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

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: 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.

Tectonic Activity: Tectonic activity at regional scales typically is concentrated in zones or belts ten to hundreds of kilometers 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). 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). 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 relatively 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 lower strain rate (Savage et al. 1999, p. 17627).

Based on the geologic history of Yucca Mountain, tectonic changes will occur at rates that are infinitesimal with respect to the repository-performance period (10,000 years), and the changes will be episodic. Episodic behavior can involve long time periods as demonstrated by formation of Yucca Mountain itself, which, 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-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).

Uplift and Subsidence: 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.: the basins are loci of chronic subsidence, and the ranges are loci of uplift or relative stability. For example, Bare Mountain, the range closest to Yucca Mountain, has undergone uplift within the 12-8 million-year (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 uplift and subsidence 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 of the crust (Smith et al. 1998, Figure 2(B)), 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; CRWMS M&O 2000k, Table 6) and subsidence will not perceptibly be advanced in the absence of slip along the block-bounding faults. The rate of subsidence of Crater Flat basin appears to have 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 a presumption of subsidence are *Excluded* from the TSPA-SR based on low consequence to dose.

Several of the Secondary FEPs presume 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, all of which involve the presumption of similar large-scale geologic effects resulting from uplift and subsidence (see the *YMP FEP Database* CRWMS M&O 2000c, Appendix D for Secondary FEPs). The general issues of folding, uplift, and subsidence are *Excluded* from the TSPA-SR based on low consequence to dose; therefore, FEPs based on these presumptions are also *Excluded* from the TSPA-SR. In the interest of specificity, however, the secondary FEPs are discussed in additional detail.

Secondary FEP "Folding, uplift or subsidence lowers facility with regard to the current water table" (1.2.01.01.01) addresses lowering of the repository elevation with respect to the current water table. If such a situation were to occur, Crater Flat and Jackass Flats would become areas of springs discharge and seasonal ponding because the repository is roughly at the same elevation as Crater Flat and Jackass Flats. The mechanisms for this to occur would involve (1) rising of the water level, (2) lowering of the repository, or (3) a combination of the effects of (1) and (2). This secondary FEP is excluded based on "low consequence to dose" as described in (1), (2), and (3) below.

(1) *Rising of the water level.* The vertical distance between the base of the repository and the saturated zone is approximately 300 m, and excursions of the water table in Plio-Pleistocene time are estimated to have been about 100 m or less (Stuckless 1996, pp. 98-99). A rise in water level, or change in head, would be related to changes in strain conditions (e.g., see Gauthier et al. 1996, with regard to earthquake-induced head changes). An additional 200-m rise in water levels, sufficient to reach the repository level, is extremely unrealistic because regional strain patterns indicate waning effects of extension east of Death Valley (inferred from Fridrich 1999, p. 191). Additionally, the horizontal geodetic strain-accumulation rate in the Yucca Mountain region is low, at the rate of about <2 mm/yr (Savage et al. 1999, p. 17627, strain rate reported as nanostrain/yr).

(2) *Lowering of the repository.* 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 rate of subsidence (i.e., lowering of the repository) is insignificant compared to the distance separating the repository and the water table.

(3) *Combination of effects.* 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 magnitude 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 the *YMP FEP Database* CRWMS M&O 2000c, Appendix D). 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 is the most significant factor affecting infiltration rates and which also 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 is not likely to be significantly influenced by rates of tectonic-induced slope change or local base-level subsidence. The change in percolation flux is not likely to be distinguishable from the change in infiltration caused by climate change. This Secondary FEP is, therefore, *Excluded* from the TSPA-SR based on low consequence to dose.

Folding: "Folding, uplift or subsidence," as used in the FEP 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 (10,000 years) is negligible.

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. Normal-fault movements at Yucca Mountain may also be associated with extension across fault planes. Hanging-wall rollover occurs as the extension and vertical displacement occurs along a fault plane and segments of hanging wall near the fault plane fracture and turn down into the fault plane. Consequently, rollover folds at Yucca Mountain affect relatively small segments of the downthrown blocks, and the rollover folds are typically associated with increased fracturing as the block-bounding fault is approached. The rollover segments have been mapped, and the repository design considers this geologic feature.

Folding at Yucca Mountain 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 0.001-0.03 mm/yr (CRWMS M&O 2000k, 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 (see Assumption 5.1 of this AMR (ANL-WIS-MD-000005)), resulting in a steepening of about 2° in one million years. Such a minor change will not significantly affect infiltration or groundwater flow characteristics. Without a change in infiltration or groundwater flow characteristics, folding does not provide a mechanism for significantly affecting dose. Consequently, FEPs predicated on an presumption of folding during the performance period are *Excluded* from the TSPA-SR based on low consequence to dose.

The Secondary FEP 1.2.01.01.03, "Tectonic folding alters dip of tuff beds, changing percolation flux" (*see the YMP FEP Database* CRWMS M&O 2000c, Appendix D), is predicated on the presumption that dip constrains percolation flux and is predicated on the presumption that flux is primarily controlled by the strata-confined matrix permeability, as opposed to flow through fractures. At Yucca Mountain, tectonic folding is related to the extensional tectonic setting and can result in hanging-wall rollover in the vicinity of faults. The potential for increased permeability in hanging-wall rollover segments from fracturing far outweighs the significance of matrix permeability in rollover segments. Given 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 their orientation (i.e., an increase in fold-limb dip associated with rollover) becomes a significant factor in local percolation flux. Given the low rate of normal-fault activity at Yucca Mountain and the small offsets per slip event, any increase in hanging-wall rollover that would affect 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 *Excluded* from the TSPA-SR based on low consequence to dose. 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 2000e).

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 (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 into the crust near Yucca Mountain from source depths at about 60 km (Crowe et al. 1995, pp. Figure 5.1). These observations can be interpreted to indicate a waning tectonic setting (Crowe et al. 1995, pp. 5-15 and 5-16).

Any significant change in regional strain rates and orientation at Yucca Mountain would likely be signaled by increased heat flux (Lachenbruch and Sass 1978, pp. 224) and by a prolonged period of seismicity. Hypothetically then, tectonic activities have the potential to result in changes in geothermal conditions. This is addressed as the Secondary FEP 1.2.01.01.01 "Tectonic changes to local geothermal flux causes convective flow in SZ and elevates water table" (see the *YMP FEP Database* CRWMS M&O 2000c, Appendix D).

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 existing geothermal gradient could be changed rapidly in the present tectonic setting, however, if a large volume of magma were 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, 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. Because of the time required for development, geothermal-gradient changes do not provide a mechanism sufficient to affect the repository performance. Because there would be no affect on repository performance, there would be no significant change to the expected dose. Consequently, this Secondary FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

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 pre-existing fractures may significantly change the flow and transport paths. Newly formed and reactivated fractures typically result from thermal, seismic, or tectonic events.

Screening Decision and Regulatory Basis: *Included* in the TSPA-SR—Does not satisfy a screening criterion (for existing fracture characteristics).

Excluded from the TSPA-SR—Low consequence to dose *(Preliminary)* (for changes of fracture characteristics due to thermal loading, tectonic activity, or seismicity).

Potential Consequence: Groundwater flow and transport of any released radionuclides in the Yucca Mountain region may take place along fractures. Flow and transport are influenced by fracture characteristics such as orientation, aperture, asperity, fracture length, connectivity, and the nature of any fracture linings or fillings. Generation of new fractures and reactivation of pre-existing fractures may significantly change the fracture characteristics and, thereby, alter the flow and transport paths, thereby affecting dose. These changes could also alter the groundwater flux through the repository and the amount of water contacting elements of the EBS or the waste packages and, thereby, alter the waste form and/or performance characteristics of these repository elements.

Screening Argument: Fractures and the associated Secondary FEPs for existing fracture characteristics are *Included* in the TSPA-SR, as described in the TSPA Disposition. Screening arguments for *Excluded* from the TSPA-SR *(Preliminary)* changes in fracture characteristics follow.

The following screening argument considers the potential effects of changes to existing fractures in the UZ and the SZ, the potential for the reactivation of existing fractures, and the potential for creation of new fractures. Available analyses for the UZ, as discussed below, indicate that changes in the existing fracture characteristics would have no significant impact on flow conditions. The analyses for the SZ are discussed below, and include uncertainties in the data distribution that minimize the significance of future changes in the existing fracture properties. The reactivation of fractures and the development of new fractures have been shown qualitatively to be of low probability based on results of the PSHA (USGS 1998). Strain is more likely to affect existing features rather than to create new fractures as evidenced by field observation of reactivation features and the geologic history of Yucca Mountain.

The effects of changes to fracture systems in the UZ 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 2000e). This analysis is a key support document for the screening decision for the "Fractures" FEP and will be discussed in the following text. The UZ sensitivity analyses are performed with the nominal UZ three-dimensional flow model and are based on a dual-permeability, active-fracture concept. An active-fracture concept accounts for the possibility that only a portion of the fracture network is hydraulically active in conducting water, whereas other fractures are bypassed. The analyses use several conservatisms that, together, provide bounding cases for determining whether changes in fractures will significantly impact repository performance. The analyses are based on the changing of fracture apertures that could be the result of strain conditions or other factors. Given a change in fracture aperture, other fracture hydrologic properties (permeability, capillary pressure, and porosity) are estimated through the use of theoretical models. The UZ analyses in CRWMS M&O (2000e) indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration.

The results of the sensitivity study are used to support multiple FEPs that examine potential effects due to changes in stress conditions (see Section 6.2.15 "Hydrologic response to seismic activity" (1.2.10.01.00); Section 6.2.19 "Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock" (2.2.06.02.00); and Section 6.2.20 "Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults" (2.2.06.02.00)). Because the sensitivity study is based on the net changes in fracture apertures, the proximal cause of the change in fracture aperture (e.g., thermal changes, seismic-induced, or tectonic events) is insignificant, as long as the expected change in apertures falls within the range of the fracture apertures examined in the analysis. The sensitivity study considers two bounding cases, with fracture apertures being varied by 0.2 times to 10 times the existing apertures for each of the bounding cases. Each of the cases is examined for present-day climate and for long-term average climate (transitional between present-day and glacial climates).

The sensitivity analyses include two bounding cases: (1) the change in fracture properties occurs over the entire UZ domain (fault zones and fractured rock), or (2) a more realistic case: the effect of fault displacement is limited to fracture-property changes in fault zones. These are modeling cases chosen to bound a presumed range of fracture-aperture changes resulting from fault movement. There are no direct observations for Yucca Mountain that relate stress caused by fault displacement to strain and resultant changes in fracture aperture. The bounding cases are used to simulate a response beyond that of the expected geologic response.

Two conservatisms are present in the sensitivity analysis. The first conservatism is that the increase in fracture aperture used in the analysis is based on an presumed fault displacement that is greater than those that are observed along the block-bounding faults or that, based on the PSHA (USGS 1998), are likely to occur. This conservatism applies to both of the bounding cases used for the analysis. The second conservatism involves the distribution of strain over the entire UZ domain in response to fault displacement, and it applies only to the first bounding case. Because it is a bounding case, the response exceeds the expected geologic response.

The first conservatism lies in the estimated fracture aperture for the bounding case. A maximum ten-fold increase in fracture aperture is selected as a modeler's upper-bounding value and was justified in CRWMS M&O (2000e). The justification cites distance-strain relationships derived from models for a 1-m displacement along a strike-slip fault (used as an analogue, though not directly representative of normal-fault response) at Yucca Mountain and for a 1-m displacement on a theoretical normal fault. The changes in fracture apertures for the sensitivity analysis are derived by presuming a 10-m fault movement along the Solitario Canyon and multiplying the strains cited in the justification. The first conservatism results because the presumed 10-m displacement is conservative when compared to probabilistically determined and observed fault displacements.

Although the sensitivity analysis presumes a fault-displacement bound of 10 m, the results of the PSHA (USGS 1998, Figures 8-2 and 8-3) associate median fault displacements of approximately 3 m, and 85th fractile fault displacements of 5 m, on the block-bounding faults to the 10^{-8} annual-exceedance probability (see Assumptions 5.4 and 5.5 of this AMR (ANL-WIS-MD-000005)). Additionally, the maximum measured single-event Quaternary displacement (i.e., during the past 1.6 million years) on the Solitario Canyon fault is only 1.3 m (Ramelli et al. 1996, Table 4.7.3).

The second conservatism in the sensitivity analysis is in the conditions of the first bounding case: that a fault displacement could result in a "change in fracture properties occurring over the entire UZ domain." Field observations indicate the presence of gouge and brecciated zones only in limited proximity to fault planes. This suggests that much of the strain will be mechanically dissipated within or near the fault planes. For instance, in the Solitario Canyon fault zone in the Enhanced Characterization of the Repository Block (ECRB) Cross Drift, the total cumulative displacement is approximately 260 m, but the gouge and brecciated zones are limited to less than 20 m from the fault (Mongano et al. 1999). Similarly, the Dune Wash fault, as exposed in the ESF, exhibits a cumulative offset of 65 m (Sweetkind et al. 1997, Table 21), but the zone of increased fracture frequency in the vicinity of the fault is only 6 to 7 m wide (Mongano et al. 1999). A third example is the observation of the Sundance fault in the ECRB Cross Drift. The Sundance fault has a presumed, though indeterminate, cumulative displacement of several meters. However, the footwall rock is intact at a distance of only 10 cm from the fault plane, and the hanging wall is slightly more fractured, with an intensely fractured zone about 1 m thick (Mongano et al. 1999). Distribution of the strain only in fault zones is used as the second, lower bounding case in the sensitivity analysis. Based on the ECRB Cross Drift observations, this second bounding case represents a lower, and more realistic, bound on the distribution of strain.

The UZ sensitivity analyses (CRWMS M&O 2000e, Section 7) indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration. The analyses presented in CRWM M&O (2000e) are evaluated for two climate conditions. A consistent infiltration rate is chosen for each analysis so that only the effects related to changes in fracture aperture are evaluated. The analyses show that the wetter climate conditions do impact the transport times. Regardless of the fracture apertures used in the sensitivity study, the principle factor influencing flux through the UZ is infiltration at land surface, which is linked directly to climatic conditions. The TSPA-SR includes a range of climatic conditions ranging from present conditions to wetter conditions associated with glacial periods. Consequently, changes in fracture aperture represent an insignificant effect compared to the influence of climate change.

The SZ model uses the concept of flowing intervals, based on YMP site data, that indicates that only some of the fractures within the saturated zone contribute to the flow. A flowing interval is defined as "a fractured zone that transmits flow in the SZ." Additionally, the SZ model implicitly includes fracture zones in the nominal case through consideration of horizontal anisotropy in permeability in the fractured volcanic units downgradient of the potential repository (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.7.1). Additionally, the SZ model also considers three cases of groundwater flow for both the horizontal isotropic and horizontal anisotropic conditions, resulting in six alternative groundwater flow fields (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.6.3.2).

Radionuclide transport is dependent on the flowing-interval porosity, the flowing-interval spacing, and the effective diffusion coefficient. (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.5.2). The SZ flow model addresses the uncertainty for each of the three parameters (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.7.2).

The determination of flowing-interval spacing potentially affects the matrix-diffusion processes in the SZ (*Probability Distribution for Flowing Interval Spacing* ANL-NBS-MD-000003 CRWMS M&O 2000p, Section 1.0). In particular, the probability distribution of flowing-interval spacing used in the SZ model likely underestimates the effect of matrix-diffusion processes in the SZ transport model because of the possible overestimation of the flowing-interval spacing (*Probability Distribution for Flowing Interval Spacing* ANL-NBS-MD-000003 CRWMS M&O 2000p, Section 1). Overestimation occurs because the number of fractures that contribute to a flowing interval cannot be determined from the available data. Because each flowing interval probably has more than one fracture contributing to it, the true flowing-interval spacing could be less than the spacing determined from the probability distribution.

Future seismic activity could redistribute strain within the system. Redistribution of strain could open new fractures and close some existing fractures, as presumed by Gauthier et al. (1996, p 163). The SZ model does not address these changes explicitly. However, because of the large, existing uncertainty considerations for the flow field and because of the conservatism in the flowing-interval spacing used for the SZ analyses, the effect of opening or closing of fractures in the SZ would be of no significance to flow-and-transport characteristics. Because flow characteristics in the SZ are not significantly changed, dose is not significantly changed.

The UZ sensitivity analyses and the SZ model consider only the existing fracture network. However, reactivation of fractures and creation of new fractures could theoretically result from thermal or seismic activity, fault displacements, or a change in the tectonic setting.

Although it does not directly address the reactivation of fractures or the creation of fractures, the PSHA (USGS 1998) examines the probability of movement along existing fractures with no measurable cumulative displacement and the development of small-scale displacements in intact rock. The tectonic strain rate controlling the seismic and fault-displacement events leading to the small-scale displacements was evaluated as an uncertain parameter in the PSHA, and the uncertainty in the tectonic rate is, thereby, reflected in the PSHA results (see Assumption 5.1). Consequently, the results can be used to infer the likelihood of reactivation of existing fractures and the creation of new fractures. This inference of applicability of the results of small-displacement probabilities to fracture probabilities is possible because of the definition of fractures.

According to the NRC (1999a, p. 55), fractures are characterized by motion perpendicular to the fracture walls (extension fractures), by motion parallel to the fracture walls (shear fractures), or by very small displacement normal to their surfaces and little or no displacement parallel to their surfaces (joints). The range of displacements extends upward to magnitudes that characterize faults, which typically originate as shear fractures capable of fracturing across discontinuities. According to Bates and Jackson (1987, p. 257), fracture "is a general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. Fracture includes cracks, joints, and faults." Consequently, fractures involve a range from no displacement up to and including small-scale movement. Tectonically induced strain can be accommodated in several ways including the formation of new fractures and/or movement on existing fractures.

The PSHA (USGS 1998, p. 8-7 referring to intact rock, or condition "d" at Points 7 and 8: (see the subheading Fault Displacement Evaluation in Section 6.2.3 for Point descriptions)) indicates that the probability of a movement (i.e., minimal displacement) developing in intact rock has less than a 10^{-8} annual-exceedance probability (see Assumption 5.4 of this AMR (ANL-WIS-MD-000005)). By inference, this corresponds to the development of new fractures. The PSHA (USGS 1998, Figures 8-10 and 8-13) indicates that fractures in the current repository area with no measured displacements can be expected to experience on the order of 0.1 to 1 cm of displacement at a 10^{-8} annual-exceedance probability. By inference, this corresponds to the reactivation of fractures. These small-scale displacements along existing fractures and in intact rock examined in the PSHA, at some undefined scale of movement, begin to fall within the range of the definition of fractures, as described above. By inference from the PSHA, the development of new fractures due to seismic activity and associated fault displacement is qualitatively inferred to be of low probability. It can also be inferred that movement along existing fractures is more likely than development of new fractures, an inference that is directly supported by field observations and consideration of the geologic history of Yucca Mountain.

Field observations indicate that the rock at Yucca Mountain is highly fractured and that existing fractures and joints have been subject to reactivation. Evidence for reactivation of joints includes the presence of thin breccia zones along cooling joints and observable slip lineations along joint surfaces (Sweetkind et al. 1996). Cooling joints originally formed as tensional openings, having only face separation, not shear. However, thin selvages of tectonic breccia are often present along the trace of cooling joints, indicating later slip. Based on these field observations, the fracture network appears to act as a significant pre-existing weakness in the rock mass that can accommodate extensional strain through distributed slip along many reactivated joints. Coupled with the results of the PSHA for movement in intact rock, it would appear that changes in strain are more likely to be accommodated along existing fractures rather than to initiate new fractures.

Fractures could also theoretically be created by mechanisms not directly related to seismicity or fault displacements, as examined in the PSHA, including changes in the stress field related solely to tectonism, without attendant seismicity or fault displacement (see Assumption 5.1 of this AMR (ANL-WIS-MD-000005)).

Based on the geologic history of Yucca Mountain, tectonic changes, and hence changes in the stress field leading to fracture development, would occur at rates that are infinitesimal. Savage et al. (1999) present an evaluation of the strain-accumulation rate at Yucca Mountain, Nevada, for the period from 1983 to 1998, and address alternative interpretations by Wernicke et al. (1998) that suggest greater strain-accumulation rates. Regardless of the existing strain-accumulation rate, the existing fracture characteristics at Yucca Mountain have developed over an extended period and over a varying range of stress-and-strain conditions. For example, the development of Yucca Mountain itself, including deposition of the tuff layers, block faulting, and subsequent development of cooling joints and fractures, 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 and 1312), and the rate of regional tectonism has decreased greatly since late Miocene (inferred from Fridrich et al. 1999). The stress conditions associated with these earlier processes vary considerably from existing conditions. Consequently, unless stress vectors acting on Yucca Mountain were to deviate markedly and rapidly from those acting (either locally or regionally) within the past few million years (see Assumption 5.1 of this AMR (ANL-WIS-MD-000005)), the shear strength of intact rock will not be exceeded (i.e., new fracturing will not be initiated) due to the presence of existing fracture sets favorably oriented to accommodate increased stresses and strains.

In summary, the available analyses for the UZ and SZ flow models indicate that changes in the fractures would have no significant impact on flow conditions. The potential changes to fracture systems in the UZ have been conservatively bounded (i.e., strain effect affects the entire UZ in the same manner, rather than t-he mixed effect of opening and closing of features) in a sensitivity study that indicates no significant impact to flow-and-transport characteristics in the UZ. Furthermore, the presence of the drip shield would minimize the impact of any increased flux in the UZ during the repository-performance period, because it would continue to minimize water flow onto the waste packages, regardless of any changes in flow conditions or climate. Analysis for the SZ incorporates existing uncertainties in the data distribution, so changes to the existing fracture system would have an insignificant effect on flow-and-transport characteristics relative to the existing modeled flow systems. The development of new fractures has been shown qualitatively to be of low probability based on results of the PSHA. Based on site observations of fracture distribution and characteristics, the tendency is for strain to cause reactivation of existing features rather than creation of new fractures. Consequently, changes in fracture characteristics do not provide a mechanism to significantly change the dose.

The evaluation of changes to fracture systems relies upon conclusions that have been designated as TBV in CRWMS M&O (2000e). Therefore, change to existing fractures, reactivation of fractures, and creation of new fractions is *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose. The presence and effects of existing fractures and associated uncertainties are *Included* in the TSPA-SR.

TSPA Disposition: The existing fracture characteristics are *Included* in the TSPA-SR for both the UZ and SZ.

The UZ flow model and its submodels are built on the current geological conceptual model. It uses a continuum approach, and fracture matrix interaction is addressed through the use of dual-permeability considerations, modified to address active-fracture considerations to represent effects of flow channeling and fingering through fractures, which may limit flow into the matrix system. Inputs include (1) fracture properties (frequency, permeability, van Genuchten parameters, aperture width, porosity, and interface area) for each UZ model layer; (2) matrix properties (porosity, permeability, and the van Genuchten parameters) for each UZ model layer; (3) thermal and transport properties for each UZ model layer; and (4) fault properties (matrix and fracture parameters) for each of the major hydrogeologic units *(Unsaturated Zone Flow and Transport Model Process Model Report* TDR-NBS-HS-000002 CRWMS M&O 2000l, Section 3.7.2). The abstraction to the TSPA-SR includes a total of nine flow fields, consisting of three infiltration cases (lower, mean, and upper) within each of three climate states (present-day, monsoon, and glacial transition), and one perched-water model.

The SZ model uses an effective continuum representation of fracture permeability (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.5.1). This approach is taken for a variety of reasons: (1) the exact characterization of hydraulic and geometric properties of fractures necessary to construct an accurate, discrete-fracture model does not exist for Yucca Mountain; and, (2) at Yucca Mountain, studies of densities and spacing of flow intervals generally indicate that flow occurs through fracture zones (*Probability Distribution for Flowing Interval Spacing* ANL-NBS-MD-000003 CRWMS M&O 2000p, Section 5.0), with fracture zones located in various geologic units, and, in most cases, no single zone dominates the flow through a well. The SZ model uses the concept of flowing intervals, defined as "a fractured zone that transmits flow in the SZ." The concept of flowing intervals is based on site data that indicates that only some of the fractures within the saturated zone contribute to the flow. Additionally, the SZ model nominal case implicitly includes fracture zones through consideration of horizontal anisotropy in permeability in the fractured volcanic units downgradient of the potential repository (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.7.1). The SZ model also considers three cases of groundwater flow for both the horizontal isotropic and horizontal anisotropic conditions, resulting in six alternative groundwater flow fields (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.6.3.2). The SZ model is abstracted to the TSPA-SR by performing radionuclide transport simulations that use a constant, unitary radionuclide flux at the "upstream" end of the SZ. The results are obtained by running the site-scale SZ flow-and-transport model for each stochastic realization and saving the results for later use by the TSPA-SR simulator (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.6.3).

Therefore, the presence and effects of existing fractures and associated uncertainties are *Included* in the TSPA-SR. The effects of changes to fracture systems (from tectonic activity, faulting, and seismicity) are *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose as previously discussed.

IRSR-Issues: See Attachment II

Related AMRs: *Probability Distribution for Flowing Interval Spacing* ANL-NBS-MD-000003 (CRWMS M&O 2000p)

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

Features, Events, and Processes in UZ Flow and Transport ANL-NBS-MD-000001 (CRWMS M&O 2000q)

Features, Events, and Processes in SZ Flow and Transport ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: The Screening Argument above embodies the results of analyses that examined the consequence to dose and the geologic realities of fracturing. Additional data on the fault-and-fracture relationships are available to support the conclusions drawn above and provide additional support to the preceding argument.

The potential for significant changes in fracture apertures in response to geologic processes was investigated in the screening argument for the FEP "Fractures" (1.2.02.01.00). The conclusions drawn were based on site data that are the source for the development of a suite of parameters used to characterize fractures. To provide additional context for the preceding argument, examples of the types and sources of data available are provided below.

An analysis of fracture apertures is available from the ECRB Cross Drift Study (Mongano et al. 1999). The largest aperture recorded was 520 mm. Approximately 64 percent of the observed fractures exhibited "zero" aperture. Of the greater than 1800 fractures measured, only 40 apertures, or about 2 to 3 percent, were measured as greater than 20 mm. The remaining apertures were 20 mm or less.

The relationship of fractures smaller than 1 m in length to faults was evaluated by visual examination of every fault in the ESF (Sweetkind et al. 1997, p. 68) that could be correlated with a fault mapped at the land surface (Day et al. 1998a). Four principal conclusions listed below provide further evidence that the magnitude and distribution of the effects of changes in fracture aperture are conservative. Based on observations in the ESF (Sweetkind et al. 1997, pp. 68, 71), four conclusions regarding fault-to-fracture relationships can be made:

- The width of the zone of influence on fracture frequency in the immediate vicinity of a fault is, in general, quite narrow, ranging from less than 1 m to about 7 m from a fault.

- The width of the zone of influence in the immediate vicinity of a fault correlates, in a general way, with the amount of cumulative fault offset. Therefore, faults with the largest potential future displacement are the most likely to influence the potential repository block. Faults with tens of meters of cumulative offset (e.g., faults at ESF Stations 11+20 and 70+58) have zones of influence that range up to 6 to 7 m wide. The limited available data from block-bounding faults are not definitive regarding the nature of attendant fracturing. Intrablock faults with very small amounts of cumulative offset (1 to 5 m) have zones of influence that are 1 to 2 m in width.

- The width of the zone of influence around a fault does not appear to be related to depth, at least within the ESF. The width of the zones of influence is similar for small faults observed along the North Ramp, where overburden is 50 to 60 m thick, as it is for small faults observed elsewhere in the ESF, where overburden thickness is two to three times greater than at the North Ramp. However, upward-splaying faults can result in apparent broad zones of influence at land surface because of the overlap of fractured zones surrounding individual fault splays.

- The amount of deformation associated with faults appears, in part, to be dependent upon which lithologic units are faulted. In the ESF, overall variability in the frequency of fractures 1-m long or longer is primarily a function of lithology, not proximity to faults (Sweetkind et al. 1997, p. 68). Each lithostratigraphic unit at Yucca Mountain has characteristic fracture attributes, including predominant orientations, spacing, trace length, and joint type (Sweetkind et al. 1997, p. 76); and each is unique in its ability to deform by distributed slip. The result is stratigraphic control of structural geometry—what may be a discrete break in one lithostratigraphic unit may be a broad zone of distributed deformation in another. Consequently, the modeling case of "mountain-scale" distribution of changes in fracture aperture is considered to be conservative.

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, 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 and Regulatory Basis:

Included in the TSPA-SR—Does not satisfy a screening criterion (for existing fault characteristics).

Excluded from the TSPA-SR—Low consequence to dose *(Preliminary)* (for changes of fault characteristics), Low probability (for formation of new faults)

Potential Consequence: Geologic studies and recurrent seismicity show that faulting is an ongoing tectonic process at and near Yucca Mountain (Whitney 1996). Faulting may occur when differential stress exceeds the shear strength of rock or of a preexisting fault or fracture. Movement along existing fractures and faults is more likely than formation of new fractures or new faults if the preexisting fault or fracture is favorably oriented with respect to the applied stress field. Faulting is considered to be a potentially disruptive process with effects that include sudden changes in the geometry of rock adjacent to a fault that are potentially relevant to the hydrology and integrity of the potential repository. Faulting may locally alter the permeability in the rock mass, alter or short-circuit the flow paths and flow distributions close to the repository, and create new pathways through the repository. New faults or displacements on existing faults (reactivation) may enhance the groundwater flow, thus decreasing the transport times for potentially released radionuclides. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and the waste packages, leading in turn to the potential for release of radionuclides.

Screening Argument: Existing fault characteristics are *Included* in the TSPA-SR, as described in the TSPA Disposition. Changes in the fault characteristics are *Excluded* from the TSPA-SR *(Preliminary)*, as discussed below. The following screening argument addresses three areas of concern: changes due to faulting that might affect the hydrologic properties, the development of new faults and/or displacements on existing faults, and the potential for faults to damage waste packages.

Faulting 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 the FEPs "Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults" (2.2.06.02.00), see Section 6.2.20; and "Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock" (2.2.06.01.00), 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 2000e, Sections 6.2.2.2 and 6.2.2.3)

The UZ sensitivity analyses are performed with the nominal UZ three-dimensional flow model and are based on a dual-permeability, active-fracture concept. An active-fracture concept accounts for the possibility that only a portion of the fracture network is hydraulically active in conducting water, whereas other fractures are bypassed. The analyses use several conservatisms that, together, provide bounding cases for determining whether changes in fractures will significantly impact repository performance. The analyses are based on the changing of fracture apertures that could be the result of strain conditions or other factors. Given a change in fracture aperture, other fracture hydrologic properties (permeability, capillary pressure, and porosity) are estimated through the use of theoretical models. The UZ sensitivity analyses (CRWMS M&O 2000e) indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, and increased fracture apertures applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration.

The UZ sensitivity study (CRWMS M&O 2000e) includes two bounding cases: (1) that changes in fracture properties occur over the entire UZ domain (fault zones and fractured rock), or (2) that the effects of fault displacement are limited to fracture-property changes in fault zones. These are modeling cases chosen to bound a presumed range of fracture-aperture changes resulting from fault movement. There are no direct observations for Yucca Mountain that relate stress caused by fault displacement to strain and resultant changes in fracture aperture. The bounding cases are used to simulate a response beyond that of the expected geologic response. For each bounding case, the analysis evaluates fracture apertures at 0.2 times and 10 times the existing fracture aperture and also evaluates these conditions for present-day and transitional-climate conditions. The second bounding case (effects of fault displacement limited to fault zones) is applicable to the discussion for the FEP "Faulting" (1.2.02.03.00), and it is justified based on conclusions by Sweetkind et al. (1997, pp. 68, 71) and field observations by Mongano et al. (1999), described as follows.

Conclusions from Sweetkind et al. (1997, pp. 68, 71) suggest that faulting and fracturing are spatially related. The first conclusion is that the width of the zone of influence on fracture frequency in the immediate vicinity of a fault is, in general, quite narrow, ranging from less than 1 m to about 7 m from faults. The second conclusion is that the width of the zone of influence in the immediate vicinity of a fault correlates, in a general way, with the amount of cumulative fault offset. Therefore, faults with the largest potential future displacement are the most likely to influence the potential repository block. Faults with tens of meters of cumulative offset (e.g., faults at ESF Stations 11+20 and 70+58) have zones of influence that range up to 6 to 7 m wide. Intrablock faults with very small amounts of cumulative offset (1 to 5 m) have zones of influence that are 1 to 2 m in width.

The presence of gouge and brecciated zones only in limited proximity to fault planes, as described immediately below, suggests that much of the strain will be mechanically dissipated within or near the fault planes. For instance, in the Solitario Canyon fault zone in the ECRB Cross Drift, the total displacement is approximately 260 m, but the gouge and brecciated zones are limited to less than 20 m (Mongano et al. 1999). Similarly, the Dune Wash fault as exposed in the ESF exhibits a cumulative offset of 65 m (Sweetkind et al. 1997, Table 21), but the zone of increased fracture frequency in the vicinity of the fault is only 6 to 7 m wide (Mongano et al. 1999). A third example is the Sundance fault in the ECRB Cross Drift. The Sundance fault has a presumed, though indeterminate, displacement of several meters. However, the footwall rock is intact at a distance of only 10 cm from the fault plane. The hanging wall of the Sundance fault is slightly more fractured, with an intensely fractured zone about 1 m thick (Mongano et al. 1999).

A conservatism for the sensitivity study lies in the estimated fracture aperture for the bounding case. A maximum ten-fold increase in fracture aperture is selected as a modeler's upper-bounding value and was justified in CRWMS M&O (2000e). The justification cites distance-strain relationships derived from models for a 1-m displacement along a strike-slip fault (used as an analogue, though not directly representative of normal-fault response) at Yucca Mountain and for a 1-m displacement on a theoretical normal fault. The changes in fracture apertures for the sensitivity analysis were derived by presuming a 10-m fault movement along the Solitario Canyon and multiplying the strains cited in the justification. The first conservatism results because the presumed 10-m displacement is conservative when compared to probabilistically determined and observed fault displacements.

Although the sensitivity presumes a fault displacement bound of 10 m, the results of the PSHA (USGS 1998, Figures 8-2 and 8-3) indicate median and 85th fractile fault displacements of the block-bounding faults of up to 3 m and approximately 5 m for the 10^{-8} annual-exceedance probability (see Assumptions 5.4 and 5.5 of this AMR (ANL-WIS-MD-000005)). Additionally, the maximum measured single-event Quaternary displacement (i.e., during the past 1.6 million years) on the Solitario Canyon fault is only 1.3 m (Ramelli et al. 1996, Table 4.7.3).

The results of the sensitivity study (CRWMS M&O 2000e, Section 7) show that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, even for a presumed conservative condition of a ten-fold increase in fracture aperture. Because neither flow nor transport are significantly affected by changes in fracture apertures in fault zones, the effects of fracture-property changes in faults zones do not provide a mechanism to significantly affect dose. Dose is not significantly affected, so the effects of changes in fault properties on flow are *Excluded* based on low consequence to dose. The evaluation of changes to fault systems relies upon conclusions that have been designated TBV in CRWMS M&O (2000e); therefore, the designation is *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose.

The inclusion of faulting in the SZ is discussed in the TSPA Disposition below. The existing parameters include uncertainty considerations that address the potential for changes in fault characteristics. The inclusion of these uncertainties minimizes the significance of changes to fault properties in the SZ. Consequently, changes to fracture properties are *Excluded* based on low consequence to dose.

Another aspect of faulting that could be important to repository performance is the displacement on existing faults, particularly within the repository block, or the formation of new faults. Figures 8-8 through 8-13 in the PSHA (USGS 1998) 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 also selected to represent various conditions that could potentially occur within the repository area (see the subheading Fault Displacement Evaluation in Section 6.2.3 for Point descriptions). These conditions included presumed existing cumulative displacements of 2 m and 10 cm to represent existing small faults and shears, and no displacement to represent fractures (or fractures with minimal movement). The mean 10^{-8} annual-exceedance probability (see Assumption 5.4 of this AMR (ANL-WIS-MD-000005)) for these small faults, shears, and fractures is approximately 1 m, 10 cm, and <1 cm, respectively. The effects of this range of displacements, 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 2000e, Section 6.2.2.3), as discussed above. With regard to the formation of new faults, the PSHA (USGS 1998, p. 8-7 referring to intact rock (condition "d") at Points 7 and 8) indicates that mean displacements in intact rock are less than 0.1 cm for a 10^{-8} annual-exceedance probability. At 10^{-8} annual-exceedance probability, the median values are less than the mean values (see Assumption 5.4 of this AMR (ANL-WIS-MD-000005)). Consequently, the development of new faults and fractures is inferred from the PSHA to be of low probability; therefore, it is *Excluded* from the TSPA-SR.

The potential for fault displacement to shear a waste container is discussed in the FEP "Fault movement shears waste container" (1.2.02.03.00) (see Section 6.2.4), and is *Excluded* from the TSPA-SR based on the low probability of the formation of new faults in intact rock and on 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 requires asserting Assumptions 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005). The impact of fault displacement on drift integrity is examined in *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GE-000004 (CRWMS M&O 2000s), which evaluated the stress/distance relationships associated with fault displacements of 0.001 to 1 m. These displacements bound the preclosure fault displacements (based on 10^{-4} and 10^{-5} annual-exceedance probabilities) for the block-bounding faults and intrablock faults, and bound the 10^{-8} annual-exceedance probability (mean fault displacements) for points interior to the waste emplacement area.

Vibratory ground motion (seismicity) associated with faulting has been evaluated as part of other seismic-related FEPs and are summarized in the FEP "Seismic activity" (1.2.03.01.00) (see Section 6.2.5). Discussion of the potential direct impact to waste packages is deferred to the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (see Section 6.2.6). Both of these seismic FEPs are *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose.

In summary, the preceding screening arguments address three areas of concern: changes due to faulting that might affect the hydrologic properties, the development of new faults and/or displacements on existing faults, and the potential for faults to damage waste packages. The UZ sensitivity analyses (CRWMS M&O 2000e) indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, and increased fracture apertures applied over the entire UZ domain result in effects that are no more significant than other uncertainties related to infiltration. The development of new faults and fractures is inferred from the PSHA to be of low probability and is, therefore, *Excluded* from the TSPA-SR. The potential for damage from fault displacements has been *Excluded* due to low probability. Because the mechanisms that could lead to an increase in dose have been shown to be of low consequence to dose or of low probability, the FEP is *Excluded* from the TSPA-SR.

TSPA Disposition: Existing fault characteristics and uncertainties are *Included* in the TSPA-SR and are incorporated in both the UZ and SZ Flow models.

The UZ flow model incorporates many of the geologic complexities including stratigraphy, faults and associated offsets, and dipping beds using a three dimensional numerical grid (*Unsaturated Zone Flow and Transport Model Process Model Report* TDR-NBS-HS-000002 CRWMS M&O 2000l, Section 3.7.2). In particular, faults are represented using vertical or included walls 30-m thick, and faults are subdivided into four hydrogeologic units. Fracture-matrix flow and interactions with fault elements are also treated using a dual-permeability approach. Fault properties are estimated using a two-dimensional inversion of saturation, water potential and pneumatic data *(Unsaturated Zone Flow and Transport Model Process Model Report* TDR-NBS-HS-000002 CRWMS M&O 2000l, Section 3.7.2). The matrix- and fracture-parameter values for the hydrogeologic units and faults have been included through the abstraction of nine possible flow fields *(Unsaturated Zone Flow and Transport Model Process Model Report* TDR-NBS-HS-000002 CRWMS M&O 2000l, Section 3.7.5.1). 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 2000e, Section 6.2.2.3).

The three-dimensional SZ flow model incorporates the presence of existing faults through permeability considerations. Depending on their state of tension or compression, faults are modeled as either (1) zones of permeability enhancement parallel to faults and zones of permeability reduction perpendicular to faults, or (2) zones of permeability enhancement (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.2.3.4). The presence of faults and fracture zones that are not explicitly represented is implicitly included in the nominal-case flow model through consideration of horizontal anisotropy. (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.7.1). The SZ model is abstracted to the TSPA-SR by performing radionuclide-transport simulations that use a constant, unitary radionuclide flux at the "upstream" end of the SZ. The results are obtained by running the site-scale SZ flow-and-transport model for each stochastic realization and saving the results for later use by the TSPA-SR simulator (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.6.3).

The characteristics of existing faults are *Included* in the TSPA-SR, as described immediately above. The effects to UZ radionuclide transport from displacements on existing faulting have been shown to be of low consequence to dose, and the formation of new faults or fractures is of low probability. The evaluation of changes to fault systems relies upon conclusions that have been designated TBV in CRWMS M&O (2000e); therefore, the decision for changes in fault characteristics is *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose. The formation of new faults is *Excluded* from the TSPA-SR based on low probability.

IRSR-Issues: See Attachment II

Related AMRs:

Effects of Fault Displacement on Emplacement Drifts ANL-EBS-GE-000004 (CRWMS M&O 2000s).

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

Features, Events, and Processes in UZ Flow and Transport ANL-NBS-MD-000001 (CRWMS M&O 2000q)

Features, Events, and Processes in SZ Flow and Transport ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: Recurrent faulting is a tectonic process that will likely continue as discrete and/or distributed faulting throughout the 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.

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

Dip-slip Faulting: Dip-slip faulting refers to fault displacement directly along the dip of the fault plane and perpendicular to fault strike. Dip-slip faulting includes 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 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 (USGS 1998, 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, and 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 (CRWMS M&O 2000k, 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 m, 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 are analyzed and evaluated in the PSHA and are accounted for in the fault displacement analysis (USGS 1998, Section 8). As described above in the TSPA Disposition, existing faults are *Included* in the TSPA-SR.

Strike-slip Faulting: 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 faulting has occurred, 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 at Yucca Mountain 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 is associated with 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 (USGS 1998, p. 7-22, Figures 7-27 through 7-29).

Detachment Faulting: 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 Yucca Mountain 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 (USGS 1998, 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 dose and is, therefore, *Excluded* from the TSPA-SR.

<u>Fault -Displacement Evaluation</u>: 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 (USGS 1998, 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 of cumulative displacement, (2) intrablock faults having from a few meters 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.

Points 1 and 2: *Block-bounding faults, possibly seismogenic, with greater than 50 m of cumulative displacement*

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 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 thousand years (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 larger 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, a reasonable estimate of future fault displacement near the repository block is likely to be on the order of 10 cm to 1 m (USGS 1998, Figure 8-3).

Points 3, 4, and 5: *Intrablock faults having from a few meters to tens of meters of cumulative displacement*

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 than the block-bounding faults, 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 either sinistral strike-slip, or oblique-slip faults.

Points 6, 7, 8, and 9: *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*

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 listed below were considered to exist at this location and assessed. These conditions describe features encountered within the ESF and not directly correlated with specific features observed at land surface, 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 in Midway Valley east of the Bow Ridge fault on an observed fracture having no displacement in Quaternary alluvium.

The mean and median hazard results for fault displacement at the nine points are provided in the PSHA (USGS 1998, Figures 8-2 through 8-14). With the exception of Points 1 and 2, both of which are on primary block-bounding faults and will be addressed with the use of set-backs (see Section 6.2.4 for further discussion), the mean fault displacement is <0.1 cm for preclosure conditions (i.e., 10^{-4} and 10^{-5} annual-exceedance probabilities).

For postclosure conditions (i.e.,10^{-5} to 10^{-8} annual-exceedance probabilities), the hazard results at all locations have large uncertainties, and the mean results at progressively lower annual-exceedance probabilities are driven by the upper tails of the uncertainty distribution. As a result, the mean hazard at very low annual probabilities may be at or above the 95th fractile of the uncertainty distribution. Consequently, the median value for fault displacement is a more stable measure of the central tendency and is used as the basis for the FEPs screening for postclosure events (see Assumption 5.5 of this AMR (ANL-WIS-MD-000005)).

At 10^{-8} annual-exceedance probability, the mean displacement hazard for Points 3, 4, 5, and 6 and for the presumed condition of 2-m displacement at Points 7 and 8 is approximately 1 to about 2 m. At all of these locations the 15th fractile hazard is less than 0.1 cm for all annual-exceedance probabilities, indicating that the hazard is extremely low, but with large uncertainty about how low. This result indicates that the PSHA experts considered the potential for fault displacement on faults and features within the repository block to be extremely low but there was large uncertainty about how low.

Based on the PSHA results (USGS 1998, Figures 8-8 through 8-14), mean displacement on small faults (with cumulative displacements of less than 2 m) ranges from a few mm to less than 10 cm at a 10^{-8} annual-exceedance probability (See Assumption 5.4 of this AMR (ANL-WIS-MD-000005)). At these locations the median displacement hazard is below 0.1 cm for annual-exceedance probabilities less than 10^{-5}, indicating that the potential for fault displacements at these locations is negligible. 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 1 cm and as little as 0.5 cm (USGS 1998, Figures 8-10 and 8-13), and the median displacement hazard for this condition is less than 0.1 cm for all annual-exceedance probabilities. Displacement effects are likely to be of no consequence and are considered as *Excluded* from the TSPA-SR when coupled with the analysis from *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000e, Section 7).

With regard to the formation of new faults, the PSHA (USGS 1998, p. 8-7 referring to intact rock (condition "d") at Points 7 and 8) indicates that mean displacements in intact rock are less than 0.1 cm for a 10^{-8} annual-exceedance probability. At 10^{-8} annual-exceedance probability, the median values are less than the mean values (see Assumption 5.4 of this AMR (ANL-WIS-MD-000005)). Consequently, the development of new faults and fractures is inferred from the PSHA to be of low probability and is, therefore, *Excluded* from the TSPA-SR.

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 preclosure seismic design. The primary method to address faults will be fault avoidance, to the extent reasonably achievable by layout of the repository and placement of the drifts. Fault avoidance (or set-back) is also pertinent to postclosure performance assessment (see Assumptions 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005)).

The NRC provides guidance for identification and consideration of faults relevant to preclosure seismic design or postclosure repository performance 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 located 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 (CRWMS M&O 1998a, Section 1.2.1.7 and Section 1.2.1.8), will be applied to existing faults with known or suspect Quaternary-age displacements, as follows:

- 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 1998b, BCA000000-01717-1705-00011, Section 1.2.2.1.4).

The stated fault set-back distances agree with conclusions drawn from observations in the ESF (Sweetkind et al. 1997, pp. 68, 71). The first conclusion is that the width of the zone of influence on fracture frequency in the immediate vicinity of a fault is, in general, quite narrow, ranging from less than 1 m to about 7 m from the fault. The second conclusion is that the width of the zone of influence in the immediate vicinity of a fault correlates, in a general way, with the amount of cumulative fault offset. Therefore, faults with the largest potential future displacement are the most likely to influence the potential repository block. Intrablock faults with very small amounts of cumulative offset (1 to 5 m) have zones of influence that are 1 to 2 m in width. Faults with tens of meters of cumulative offset (e.g., faults at ESF Stations 11+20 and 70+58) have zones of influence that range up to 6 to 7 m wide.

Analyses to determine the effects of fault displacement on emplacement drifts, the drip shield, and the waste package have also been performed in *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GE-000004 (CRWMS M&O 2000s). Primary fault displacements ranging from 0.1 cm to 100 cm were analyzed. This range of displacements bounds the 10^{-4} to 10^{-5} annual-exceedance probabilities for block-bounding faults (Points 1 and 2 above). A displacement of 1 m roughly corresponds to the maximum measured single-event Quaternary displacement on the Solitario Canyon fault (Ramelli et al. 1996, Table 4.7.3). This range of displacements also reasonably corresponds to the 10^{-8} median annual-exceedance probability for points interior to the repository (i.e., Points 3 through 9 described previously) evaluated in the PSHA (USGS 1998, Figures 8-2 through 8-14). The results of the analysis are further discussed in the following section (Section 6.2.4) for the Primary FEP "Fault movement shears waste container" (1.2.02.03.00).

New Faults and Growth and Reactivation of Existing Faults: For purposes of this discussion, "reactivation" of existing faults is considered to be synonymous with displacements on existing faults. No differentiation of active or inactive faults is made for purposes of the FEPs analysis. Recurrent faulting is a significant tectonic process that will likely continue as discrete or distributed faulting during the repository-performance period (10,000 years) at Yucca Mountain.

With regard to processes creating new faults and/or causing displacement on 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 (0.001– 0.03 mm/yr) on faults active during the Pleistocene (CRWMS M&O 2000k, Table 6), and there is an apparent stability of intrablock faults during the Quaternary. 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 in the current tectonic-stress regime. These and alternative tectonic conditions were considered by the tectonic experts as part of the expert-elicitation process regarding fault-displacement potential for Yucca Mountain and are reflected in the fault-displacement and ground-motion hazards presented in the PSHA (USGS 1998).

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 (USGS 1998, Sections 7 and 8). Activation of a new fault strand could theoretically occur by propagation of a fracture tip, a fault splay, or a buried 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 pre-existing, aligned fractures meet each other. Although the important fault strands having a history of Pleistocene activity are mapped, 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, the probability that significant, new fault-strand activation will occur during the repository-performance period (10,000 years) is low.

The possibility of new faulting and movement on fractures was evaluated in the PSHA. With regard to the formation of new faults, the PSHA (USGS 1998, p. 8-7 referring to intact rock (condition "d") at Points 7 and 8) indicates that mean displacements in intact rock are less than 0.1 cm for a 10^{-8} annual-exceedance probability. At 10^{-8} annual-exceedance probability, the median values are less than the mean values (see Assumption 5.4 of this AMR (ANL-WIS-MD-000005)). Consequently, the development of new faults, displacement in intact rock, or activation of new fault strands is of low probability and is *Excluded* from the TSPA-SR.

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 (USGS 1998, 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 (USGS 1998, Section 6.4). Further consideration in the TSPA-SR is, therefore, *Excluded* based on low consequence to dose.

The linking of fault strands has also been evaluated in the PSHA and incorporated into the seismic and fault-displacement hazard curves presented in the PSHA (USGS 1998, Sections 7 and 8). 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 reactivation was included in the PSHA evaluations, as described above.

The PSHA (USGS 1998, Figures 8-8 through 8-13) presents the probability of additional displacement along existing small faults, existing shears, and existing fractures (i.e., with existing cumulative displacements of 2 m for small faults, 10 cm for shears, and no displacement at fractures). The mean 10^{-8} annual-exceedance probability for these features (as represented in the PSHA for Points 7 and 8, as described previously) is approximately 1 m, 10 cm, and <1 cm, respectively. At 10^{-8} annual-exceedance probability, the median values are less than the mean values. 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 2000e, Section 7), as discussed in the TSPA Disposition above. Reactivation of old fault strands is, therefore, *Excluded* from the TSPA-SR based on low consequence to dose.

6.2.4 Fault Movement Shears Waste Container (1.2.02.03.00)

FEP Description: A fault intersects the repository and a line of waste containers. That intersection shears containers by virtue of the relative offset across the containers.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA-SR— Low probability.

Potential Consequence: Faulting is considered to be a potentially disruptive process with effects that include earthquakes (i.e., vibratory ground motion) and sudden changes in the geometry of rock adjacent to a fault that are potentially relevant to the hydrology and the integrity of the potential repository. This FEP is particularly concerned with the last of these considerations. Faulting, through disruption and displacement of rock mass, has the potential to present a physical hazard to the integrity of elements of the EBS and the waste packages, leading, in turn, to the potential for release of radionuclides.

For this FEP, the discussion is limited to analyzing the potential for the offset of drifts (or tunnels) to result in the shearing (rupturing by shear forces) of waste packages.

Screening Argument: The following screening argument is based on a comparison of the potential magnitude of fault displacements to elements of the repository design (i.e., waste package-to-drift wall spacing and set-back requirements; see Assumptions 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005)). Fault displacements for the area within the repository, along intrablock faults, and along block-bounding faults are considered for preclosure (10^{-4} and 10^{-5} annual-exceedance probabilities) and postclosure (10^{-8} annual-exceedance probability) conditions (see Assumptions 5.4 and 5.5 of this AMR (ANL-WIS-MD-000005)). The range of fault displacements considered is taken from the PSHA (USGS 1998, Figures 8.2 through 8.14). For small-scale features within the waste-emplacement area (e.g., small faults and fractures) and intrablock faults, the waste package-to-drift wall distance is adequate to accommodate preclosure and postclosure movements without inducing shearing conditions (see Assumption 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005)).

For block-bounding faults, however, the use of set-backs will be required. Set-backs are a design element that potentially alleviates fault-displacement effects and can be used as the basis of the FEP-screening argument (see Assumptions 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005)). Existing set-back requirements appear to be adequate to address preclosure and postclosure fault displacements. The following applicable criteria for fault set-back for preclosure design of the facility have been developed based on engineering judgement (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).

For shearing to be a credible waste-package-damage mechanism, the magnitude of differential displacement at the package location must be greater than the waste package-to-drift wall distance. For the current repository design (see Assumption 5.3 of this AMR (ANL-WIS-MD-000005)), the vertical distance from the waste package to the drift wall is approximately 2 m, and the horizontal distance is approximately 1.5 m at the waste package centerline (CRWMS M&O 2000b, Figure 4). Consequently, the physical situation needed to induce shearing requires that the differential displacement at the waste package must be greater than 2 m vertically or 1.5 m horizontally.

The history of faulting and the nature of fault slip and its structural effects at Yucca Mountain are well known (USGS 1998; Whitney 1996). *In-situ* stress measurements indicate that faults at Yucca Mountain are at the point of failure (Stock and Healey 1988, p. 92, Stock et al. 1985, p. 8705). The PSHA (USGS 1998, Figures 8.2 through 8.14) provides the results of the expert-elicitation process as it applies to probable fault displacements. The PSHA results include consideration of uncertainty (see Assumption 5.5 of this AMR (ANL-WIS-MD-000005)).

The PSHA (USGS 1998, for Points 7d and 8d, as described under the subheading Fault Displacement Evaluation in Section 6.2.3 of this AMR (ANL-WIS-MD-000005)) indicates that there is a negligible probability ($<10^{-8}$ annual-exceedance probability) that movement greater than 0.1 cm will occur in intact rock in the waste-emplacement area. Consequently, it is inferred that shearing by new faults is of low probability because the probable mean and median displacements are significantly less than the 2-m minimum displacement required to cause shearing conditions.

The PSHA (USGS 1998, Figures 8-8 through 8-14) also addresses features within the waste-emplacement area by assessing the probability of displacement along existing small faults, shears, and fractures, as represented in the PSHA for Points 7a, 7b, 7c, 8a, 8b, and 8c, as described under the subheading Fault Displacement Evaluation of Section 6.2.3 of this AMR (ANL-WIS-MD-000005). The mean 10^{-8} annual-exceedance probability for these small faults, shears, and fractures is approximately 1 m, 10 cm, and <1 cm, respectively. The median displacements are less. Consequently, shearing of waste packages from movement along existing features within the waste-emplacement area is of low probability because the probable mean and median displacements are significantly less than 2 m, the minimum distance required to cause shearing conditions.

The PSHA (USGS 1998, Figures 8.4 through 8.7, and 8.14) also examines displacements along intrablock faults. At 10^{-8} annual-exceedance probability, the 85th fractile and mean fault displacements for intrablock faults are, with one exception, less than 2 m. The exception is for the mean fault displacement for the Drill Hole Wash fault, which is approximately 2.5 m. In all cases, the median fault displacements are all less than 1 m (see Assumption 5.5 of this AMR (ANL-WIS-MD-000005)). Consequently, shearing of waste packages from movement along existing intrablock faults is of low probability because the probable displacements are significantly less than the 2-m minimum distance required to cause shearing conditions. This conclusion is especially valid if the median fault displacement for the 10^{-8} annual-exceedance probability is considered (see Assumption 5.5 of this AMR (ANL-WIS-MD-000005)).

The preceding discussions indicate that the postclosure fault displacements in the waste-emplacement area and along the intrablock faults, inclusive of the large uncertainties in maximum displacement values, are addressed by the repository design without the use of set-backs. However, the results of the PSHA (USGS 1998) indicate that set-backs will be required to address potential fault displacements along the block-bounding faults. The adequacy of a 60-m set-back is the focus of the following discussions.

The PSHA (USGS 1998, Figures 8.2 and 8.3) provides the magnitude of possible displacements along the block-bounding faults. For the TSPA, the 10^{-4} and 10^{-5} annual-exceedance probabilities are typically used as the bound for preclosure conditions. The mean fault displacements for the 10^{-4} annual-exceedance probability (preclosure) for the Solitario Canyon and the Bow Ridge faults are both listed as <0.1cm, and the mean fault displacements for the 10^{-5} annual-exceedance probability are 32 cm and 7.8 cm respectively (USGS 1998, Figures 8.2 and 8.3). At the 10^{-8} annual-exceedance probability (postclosure), the median fault displacement for the Solitario Canyon is 3 m, and the 85th fractile value and mean value are greater than 5 m (USGS 1998,

Figure 8.3). For the Bow Ridge fault, the median fault displacement for the 10^{-8} annual-exceedance probability is 2 m, and the 85th fractile value and mean value are greater than 5m (USGS 1998, Figure 8.2). The median fault displacements of 3 m and 2 m are used as the screening basis. The possible postclosure median fault displacements along block-bounding faults are equal to or greater than the 2-m distance between the waste package and drift wall, suggesting that additional design considerations, such as set-backs from the block-bounding faults, are needed.

The 60-m preclosure set-back requirement is the focus of the following discussions. To be considered adequate to alleviate shearing conditions at the stated set-back distance, the differential displacement across the drift diameter (5 m) or along the length of a waste package (10 m) must be less than the waste package-to-drift wall distance (approximately 2 m).

The adequacy of preclosure set-back distances to address postclosure fault displacements can be evaluated by examining and extrapolating the results of *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GE-000004 (CRWMS M&O 2000s). The analyses were specifically stated to "bound[s] the mean fault displacements corresponding to an annual frequency of exceedance of 10^{-5} adopted for the preclosure period of the repository and also supports the postclosure performance assessment" (CRWMS M&O 2000s, Section 1). To bound the preclosure conditions (fault displacements of 32 cm and 7.8 cm on the Solitario Canyon and Bow Ridge faults, respectively), the analyses in CRWMS M&O (2000s) are based on fault displacements ranging from 0.1 cm to 1 m, and, for the stated range of fault displacements, effects were evaluated for set-back distances ranging from 0 to 100 m. Extrapolation of the results for a 3-m fault displacement are provided below to address the postclosure median fault displacements indicated in the PSHA.

Based on the results of the PSHA (USGS 1998 Figures 8.3 and 8.2) but not specifically addressed in the analyses (CRWMS M&O 2000s), a 1-m fault displacement along the Solitario Canyon is associated with the median fault displacement at 10^{-6} annual-exceedance probability and the 15th fractile for 10^{-8} annual-exceedance probability. For the Bow Ridge fault, a 1-m displacement is associated with the mean fault displacement for 10^{-6} annual-exceedance probability and falls above the 15th fractile for the 10^{-8} annual-exceedance probability value. The fault displacements used for the analysis presented in CRWMS M&O (2000s) overlap with the 15th to 50th fractile hazard curves for fault displacement at the 10^{-8} annual-exceedance probability (i.e., into the postclosure range) and directly support the postclosure performance assessment. However, to better and more consistently address the potential postclosure fault displacements, the results of the analyses presented in CRWMS M&O (2000s) will need to be extrapolated to a fault displacement of at least 3 m (as described above from results of the PSHA and based on Assumption 5.5 of this AMR (ANL-WIS-MD-000005)) to address the median fault displacement for the 10^{-8} annual-exceedance probability.

The analyses presented in *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GE-000004 (CRWMS M&O 2000s) presume worst-case orientations for fault-drift spatial relationships and examine varying fault-rupture lengths, rock-mass qualities, and distances from the fault. The results are expressed in graphical and table format (CRWMS M&O 2000s, Figures 6 and 7, and Table 5) and relate the magnitude of the effect to the magnitude of the fault displacement. The effects are in terms of induced rock movement, induced normal stress, and induced shear stress at the drift-center location. In general, the results indicate that the effects decrease with distance from the fault for a given set of conditions, as would be expected.

Figures 6 and 7 (CRWMS M&O 2000s) illustrate the relationship of the magnitude of induced rock movement to the magnitude of the fault displacement and show this relationship for varying distances from the fault. The term "induced rock movement" relates to the movement of the drift centerline relative to its initial starting position. For this FEP discussion, it is the distance the drift or waste package at a given location moves in response to the fault displacement. The potential for damage to waste packages exists because there is a difference in the distance moved (differential movement) from one side of the drift to the other, or from one end of the waste package to the other. If the magnitude of differential movement is sufficient to cause the drift wall to come in contact with the waste package/drip shield, then conditions conducive to waste-package shearing could occur. The magnitude of the differential displacement can be determined from the induced rock movement simply by subtracting the induced rock movement at one point from that at another.

Figure 7 (CRWMS M&O 2000s) indicates that for a 1-m displacement on the Solitario Canyon fault, induced movements at 10 m, 60 m, and 100 m from the fault are approximately 50 cm, 30 cm, and 25 cm respectively. This indicates that differential displacements over the distances between these points would be approximately 20 cm for the span from 10 m to 60m, and approximately 5 cm for the span from 60 m to 100 m.

To address a 3-m displacement, the results for the 1-m displacement must be extrapolated. However, a statement in CRWMS M&O (2000s, Section 7) warns that ". . . caution must be taken in attempting to extrapolate the results for a much longer fault length in the dip direction, say a=10,000m *[where a=fault length]*. Any significant deviation from the assumptions and input parameters listed in this analysis calls for a re-evaluation of the results presented in this analysis." The cautionary statement is added because increasing fault displacements are associated with increasing fault lengths. For the 1-m displacement analysis a maximum fault length of a=400 m is used, and is related to the depth of the repository at 300 m, which is tied to assumptions specified in the analyses (CRWMS M&O 2000s, Assumptions 5.6, 5.8, and 5.10).

With the preceding caveats, the results for the 1-m displacement are extrapolated to larger fault displacements. A 3-m fault displacement on the block-bounding faults (i.e., the median fault displacement for 10^{-8} annual-exceedance probability) would correspond to differential displacements of 60 cm for the span from 10 m to 60 m and 15 cm for the span from 60 m to 100 m, using an a value equal to 400 m. An increase in the a value would increase the displacement value. Based on the increase in the displacements shown for Figure 6 and Figure 7 (that is CRWMS M&O 2000s, Figures 6 and 7) where the a value increases from 100 m to 400 m, a four-fold increase in the a value results in a doubling of the resulting displacement. If the relationships between a value, fault displacement, and displacement in the drift are linear, then a three-fold increase in fault displacement would suggest an increase of 1.5 times the calculated differential displacements. This results in an "adjusted" differential displacement of 90 cm and 22.5 cm, respectively, for the 10-m to 60-m span and the 60-m to 100-m span.

The stated differential displacements are conservatively overstated for the conditions within the drifts. The stated differential displacements are for spans of 50 m and 40 m, respectively, while the drift diameter and the length of the waste package, approximately 5 m and 10 m, are significantly less. Consequently, differential displacements over the distance of the drift diameter and waste packages would also be proportional and significantly less. By extrapolation, differential displacement over a distance of 5 m would be on the order of a few centimeters or less.

The representativeness of the differential displacements derived from the results of *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GE-000004 (CRWMS M&O 2000s), compared to the results provided by the PSHA, can be determined by comparing the differential displacement at a distance of 100 m for a specified fault displacement (CRWMS M&O 2000s, Figure 7) to a point located 100 m east of the Solitario Canyon (USGS 1998, Figures 8.8 through 8.10).

As stated previously, the differential displacement resulting from a normal fault, for the distance from 60 m to 100 m, is 5 cm (CRWM M&O 2000s, Figure 7), which is associated with a 10^{-6} annual-exceedance probability. By extrapolation, the differential displacement for the same span for the associated 10^{-8} annual-exceedance probability was determined to be approximately 20 to 25 cm.

From the results of the PSHA (USGS 1998, Figures 8.8 through 8.10), the displacement value at 10^{-6} annual-exceedance probability for a point 100 m from the Solitario Canyon is on the order of 1 to 5 cm. For the 10^{-8} annual-exceedance probability, the displacement may range from less than 1 cm to 100 cm. The differential displacements described in the paragraph above fall within the range of displacement values provided in the PSHA.

The analysis presented in the *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GE-000004 (CRWMS M&O 2000s, Table 5 and Figure 22) did not include the analysis of the shear strength of any drift support, the drip shield, or the waste package. Consequently, even if a differential displacement occurs, material strengths must also be overcome before shearing occurs. The analysis (CRWMS M&O 2000s) provides the calculated, induced normal stress and induced shear stresses in the rock mass and indicates that stresses are on the order of tens of MPa. By contrast, the yield and tensile strengths of the materials used in the drip shield are greater than a few hundred MPa at 20°C (*Rock Fall on Drip Shield* CAL-EDS-ME-000001 CRWMS M&O 2000t, p. 5). Consequently, even if the fault displacements were sufficient to cause the drift wall to contact the drip shields, the drip shields and waste packages would offer additional resistance to shearing stresses.

Consequently, within the constraints and appropriateness of the extrapolations as cautioned above, a 60-m set-back from the fault is adequate to accommodate postclosure shearing from the block-bounding faults. Given that 2 m of differential displacement must occur across the drift prior to the onset of shearing conditions, an additional 1 m to 1.7 m of postclosure displacement (i.e., displacements greater than the median value) could be accommodated. With the use of set-backs (see Assumptions 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005)), shear stresses potentially induced on the drip shield and waste packages by fault-displacement hazards along the block-bounding faults will be mitigated with or without the use of engineered backfill. 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.

A more probable scenario than shearing is that the drift floor would shift and the waste package would be tilted, or dislodged from the emplacement pallet. Similar effects have been considered in the related Primary FEPs "Movement of containers" (2.1.07.03.00) and "Floor buckling" (2.1.07.06.00) (see the *YMP FEP Database* CRWMS M&O 2000c, Appendix D for TSPA Disposition and Screening Arguments; and *Engineered Barrier System Features, Events, and Degradtaion Modes Analysis* ANL-EBS-MD-000035 CRWMS M&O 2000u, p.52 and 54). A differential displacement of 10 cm at one end of a 5-m long waste package would cause an angle of inclination of about 1 degree, and differential displacements on the order of 10 cm would cause an angle of inclination of about 11 degrees. A tilting of the waste packages alone does not represent a potential for damage. If the tilting were sufficient to cause the waste package to drop off the emplacement pallet, the drop height would be no greater than those addressed by existing design requirements (*Preclosure Design Basis Events Related to Waste Packages* ANL-MGR-GS-000002 CRWMS M&O 2000v, Section 4.2.7 through 4.2.13).

In summary, because the effects of fault displacement are negligible or are addressed by the repository design (in this case, set-backs and or distance from the waste package to the drift wall), faulting does not provide a mechanism sufficient to shear the waste package or to release radionuclides. The differential displacements for points within the waste-emplacement area are shown by the PSHA to be less than 2 m, which is the vertical distance from the waste package/drip shield to the drift wall. At least 2 m of displacement must occur for shearing conditions to occur. For the block-bounding faults, at a 60-m set-back, the differential displacements are only on the order of a few centimeters and are insufficient to result in shearing. Damage mechanisms related to tilting of the waste package are addressed by the preclosure-design drop criteria. Therefore, this FEP is not a credible event and is *Excluded* from the TSPA-SR based on low probability.

TSPA Disposition: "Fault movement shears waste containers" is *Excluded* from the TSPA-SR, based on low probability, as discussed in the Screening Argument.

IRSR-Issues: See Attachment II

Related AMRs: *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GE-000004 (CRWMS M&O 2000s).

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: *In-situ* stress measurements indicate that faults at Yucca Mountain are at the point of failure (Stock and Healey 1988, p. 92, Stock et al. 1985, p. 8705). It is appropriate to think of the block-bounding faults as primary loci of strain accumulation. Based on fault zones observed in the ESF, existing block-bounding faults will fail and focus strain effects in the immediate vicinity of the fault zone, thereby preventing significant damage to the larger repository-block volume.

Identifying and locating 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 construction (as they have been in the ESF and ECRB Cross-Drift), adequate offset from and avoidance of the faults will be incorporated into waste-emplacement design (see Assumptions 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005)).

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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose *(Preliminary)* (for indirect effects: fault growth, new faults, changes in rock stress, disruption of drift).

Excluded from the TSPA-SR—Low consequence to dose *(Preliminary)* (for direct breaching of drip shield, emplacement pallet, and waste package).

Included in the TSPA-SR—Does not satisfy a screening criterion (for fuel-rod-cladding damage).

Potential Consequence: Seismic activity has the potential to result in movement along faults or changed rock stresses, resulting in changes in groundwater flow-and-transport properties. Ground motion associated with seismic activity has the potential to disrupt the integrity of components of the EBS or waste packages.

Screening Argument: Seismic activity is 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.

Rapid or slow fault growth and new fault formation are addressed in the FEP "Faulting" (1.2.02.02.00) and are *Excluded* from the TSPA-SR for changes to fault characteristics. Effects of the displacement of faults are addressed in the FEP “Fault movement shears waste container” (1.2.02.03.00), which is also *Excluded* from the TSPA-SR

Jointed-rock motion is addressed as seismically induced rockfall and drift degradation (as it relates to disruption of drifts) and is *Excluded* from the TSPA-SR *(Preliminary)* as addressed in the FEPs, “Rockfall (large block)” (2.1.07.01.00) and “Mechanical degradation or collapse of drift” (2.1.07.02.00). These FEPs are *Excluded* from the TSPA-SR *(Preliminary)*.

Seismic activity resulting in effects on groundwater flow, such as changes in hydraulic heads and changes in groundwater and recharge or discharge zones, are addressed in the FEP “Hydrologic response to seismic activity" (1.2.10.01.00). That FEP is also *Excluded* from the TSPA-SR *(Preliminary)*. The hydrologic effects of changes in rock stress are addressed in FEPs "Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock"

(2.2.06.01.00); "Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults" (2.2.06.02.00); and "Changes in stress (due to seismic or tectonic effects) alter perched water zones" (2.2.06.03.00). All of these FEPs are *Excluded* from the TSPA-SR *(Preliminary)*, based on low consequence to dose.

Seismic effects (such as vibration damage from ground motion) on the drip shield, emplacement pallet, waste package, and fuel-rod cladding are discussed in "Seismic vibration causes container failure" (1.2.03.02.00). Based on the results of analyses for ground-motion failure, ground-motion failure of the drip shield, and on the emplacement pallet and waste package are *Excluded* from the TSPA-SR *(Preliminary)*. Damage to the fuel-rod cladding is *Included* in the TSPA-SR.

In summary, ground motion from seismic activity has been considered in preclosure-design criteria and is reflected in repository-component design parameters (such as system-component performance requirements based on the seismic criteria specified at proposed rule 10 CFR 63 (64 FR 8640)). These criteria are reflected in the repository design being used in the TSPA-SR and are included in the TSPA-SR in terms of package performance parameters. Based on a fragility analysis, ground-motion damage of fuel-rod cladding is specifically *Included* in the TSPA-SR as part of the TSPA-SR model for ground motion with less than a 10^{-6} annual-exceedance probability.

TSPA Disposition: Seismic effects, as described above are *Excluded from the TSPA-SR (Preliminary)* for indirect effects / *Excluded* from the TSPA-SR *(Preliminary)* for direct damage of the drip shield, emplacement pallet, and waste package / *Included* in the TSPA-SR for fuel-rod-cladding damage.

IRSR-Issues: See Attachment II

Related AMRs: *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada*
ANL-CRW-GS-000003 (CRWMS M&O 2000k)

Features, Events, and Processes in UZ Flow and Transport
ANL-NBS-MD-000001 (CRWMS M&O 2000q)

Features, Events, and Processes in SZ Flow and Transport
ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: The proposed repository is expected to experience repeated vibratory ground motion from periodic earthquakes in the Yucca Mountain region. Repeated ground motion has been quantified in the PSHA (USGS 1998, Section 7). Probabilistic seismic-hazard results were obtained by integrating seismic sources, earthquake recurrence distribution, and estimated ground motion along with any associated variability and uncertainty. Thus, the ground-motion-hazard results provide statistically robust ground-motion values that can be used to evaluate stresses imposed on repository drifts, on 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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose *(Preliminary)* (for drip shield and waste package damage).

Included in the TSPA-SR—Does not satisfy a screening criterion (for fuel-rod cladding).

Potential Consequence: Repeated vibration of container and/or container impact with the drift floor, the drip shield, or other container has the potential to damage the container. Ground motion associated with seismic activity has the potential to disrupt the integrity of components of the EBS or waste packages. These events could lead to impaired container performance and/or breaching, with subsequent radionuclide release.

Screening Argument: The available seismic-analyses results indicate that preclosure ground motion (10^{-4} annual-exceedance probabilities) does not result in seismic damage. The seismic analyses indicate that, due to design, preclosure mean ground motion can be *Excluded* based on low probability of damage. As described in Section 1.3.2 of this AMR (ANL-WIS-MD-000005), low probability arguments can also be translated into low-consequence-to-dose arguments. To address postclosure ground motion (10^{-5} to 10^{-8} annual-exceedance probabilities), the discussion invokes a qualitative argument, based on existing waste-package-design drop criteria, that addresses probable failure mechanisms for postclosure ground motion (See Assumption 5.5 of this AMR (ANL-WIS-MD-000005)). The qualitative argument is supported with a quantitative analysis that relates postclosure, median ground motion to equivalent drop heights. The following discussion also addresses existing considerations in the TSPA-SR models, which minimize the consequence to dose if a failure were to occur due to postclosure ground motion. Because the postclosure ground motion is addressed qualitatively, the screening argument is based on low consequence to dose, rather than low probability.

For this FEP, *breaching* is used to imply that due to a penetration, rupture, or tear entirely through the drip shield, waste package, and fuel rod cladding, radionuclide containment can no longer be presumed. *Impairment* is being loosely defined as applying to other effects such as increased degradation rates that shorten the performance lifetime of a component. *Failure* is being defined as not "performing the intended waste-containment function" and *damage* is used generically to apply to breaching, impairment, and/or failure.

For purposes of the screening of this FEP, it is assumed that drip shields are included in the repository design (see Assumptions 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005)). It is also assumed that $10^{-4}/10^{4}$ yr is equivalent to a 10^{-8} annual-exceedance probability (Assumption

5.4 of this AMR (ANL-WIS-MD-000005)) and that median values for ground motion are used for postclosure analyses (Assumption 5.5 of this AMR (ANL-WIS-MD-000005)). The mean value and 85th fractile values for ground motion with annual-exceedance probabilities of 10^{-6} to 10^{-8} could be derived and applied to system fragilities, but the usefulness of such evaluations is constrained due to a high degree of uncertainty in the intensity of ground motion (see Assumption 5.5 of this AMR (ANL-WIS-MD-000005)). These values, while uncertain, nevertheless do reflect the current state of scientific and modeling uncertainty.

The proposed repository is expected to experience repeated vibratory ground motion from periodic earthquakes in the Yucca Mountain region. Repeated ground motion has been quantified in the PSHA (USGS 1998, Section 7). Probabilistic seismic-hazard results are obtained by integrating all of the variables of the seismic environment of the site. These variables include seismic sources (including local and regional faults), earthquake recurrence distribution, and estimated ground motion. The PSHA specifically incorporates the variability and uncertainty in these variables (USGS 1998, Section 7.1.1). Thus, the ground-motion-hazard results provide statistically robust ground-motion values that may be used to evaluate stresses imposed on repository drifts, on the EBS, and directly on waste packages during the repository-performance period (10,000 years). Ground-motion-hazard curves are contained in the PSHA (USGS 1998, Section 7, Figures 7-4 through 7-14).

Vibratory ground motion will induce stresses in the drip shields, emplacement pallets, waste packages, and fuel-rod cladding during the repository-performance period. The DOE Topical Report (YMP 1997) directs that ground motion with an exceedance probability of 10^{-4}/yr be used for the Category-2 design basis in evaluating preclosure radiological-safety performance. NRC seismic-design acceptance criteria, which DOE is committed to implement, assure no more than a 10% probability of failure (i.e., failure to perform the intended waste-containment function), given the occurrence of the design ground motion. General experience with design of nuclear-power-plant facilities to meet the NRC criteria indicates that they assure a margin-to-failure that is two to three times the design ground motion. At Yucca Mountain, the 10^{-5} ground motion is approximately 2.4 times the 10^{-4} or preclosure-design ground motion.

Preliminary (i.e., non-qualified) seismic analyses have specifically been performed for the drip shields, and for the emplacement pallets and waste packages (*Input Request for Seismic Evaluations of Waste Packages and Emplacement Pallets* CRWMS M&O 2000f). These results are preliminary and the conclusions are designated as TBV in *FEPs Screening of Process and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 (CRWMS M&O 2000g, Section 6.2.3) and *EBS Radionuclide Transport Abstraction* ANL-WIS-PA-000001 CRWMS M&O 2000h, Section 6.5.4 and 6.5.5). These analyses use peak ground accelerations and velocities, and analyze whether or not stresses imparted to the drip shield and waste package exceed stated material strengths (i.e., analysis for overstress conditions). These results show that there are no drip-shield separations associated with the 10^{-4} annual-exceedance probability ground motion, and there is no damage to the waste package and emplacement pallet.

An analysis has also been performed for the fuel-rod cladding (*Breakage of Commercial Spent Nuclear Fuel Cladding by Mechanical Loading* CAL-EBS-MD-000001 CRWMS M&O 1999d) using the seismic-fragility approach. The seismic-fragility approach involves the convolving of the ground-motion-hazard probabilities for the entire range of ground motion of interest (preclosure to postclosure) with probability of damage to a system component (the seismic fragility curve or component fragility). The result of the analysis is the risk (expressed as a probability) of damage to the component during the repository performance period (10,000 years). Based on the analyses presented in *Breakage of Commercial Spent Nuclear Fuel Cladding* CAL-EBS-MD-000001 CRWMS M&O (1999d), the probability (risk) of damage to fuel-rod cladding was 1.1×10^{-6}. The fragility curve is treated as a step function (i.e., damage either did or did not occur), and, based on the analysis, damage is associated with ground motion having a 10^{-6} to 10^{-7} annual-exceedance probability. Consequently, there is no indication of cladding failure for preclosure ground motion, although postclosure ground motion does result in damage that is *Included* in the TSPA-SR nominal case (see TSPA Disposition below).

None of these analyses directly justifies a probabilistic exclusion of breaching or impairment resulting from ground motion (i.e., seismic activity) occurring with an annual-exceedance probability of 10^{-6} to 10^{-8} (low probability events potentially subject to analysis as part of the postclosure evaluation). Nor do these analyses indicate the type of related damage that may occur at these lower-probability events (e.g., stress cracking as opposed to breach of the waste package). On a qualitative basis, the significance of ground motion with 10^{-6} or lower annual-exceedance probability is evaluated by considering the reasonable failure mechanisms.

For postclosure ground motion, seismic-related breaching of the drip shield and waste package could potentially occur due to rockfall or collision of the waste package with other system components such as the emplacement pallet or drip shields. Container-to-rock wall contact is precluded due to the presence of the drip shields. Container-to-rock wall contact was initially listed in the FEP description based on a design for installing the waste packages in vertical boreholes, which is no longer under consideration (see Attachment II, "Container failure induced by microseisms associated with dike emplacement," Secondary FEP 1.2.03.02.01),

Based on the analysis related to the Primary FEP "Rockfall (large block)" (2.1.07.01.00) (see Section 6.2.17 of this AMR (ANL-WIS-MD-000005)), it does not appear credible that the drip shield would be breached, because the drip shield has been designed to withstand up to a 6-MT rockfall. A reasonable failure mechanism for the waste package would involve its becoming detached from the emplacement pallet and colliding with another waste package or impacting the drip shield. However, the design criteria for handling the uncanistered, spent-nuclear-fuel waste packages indicate that the packages must be able to withstand a 6-MT rockfall onto a horizontal waste package (*Uncanistered Spent Nuclear Fuel Disposal Container System Description Document* SDD-UDC-SE-000001, CRWMS M&O 2000w, Criterion 1.2.2.1.1). The design criteria also specify that a waste package withstand a 2.3-MT impact of an object falling 2 m onto the end of the waste package, a 2-m drop of the waste package in the vertical position, and a 2.4-m drop of the waste package in the horizontal position (*Preclosure Design Basis Events Related to Waste Packages* ANL-MGR-GS-000002 CRWMS M&O 2000v, Section 4.2.7 through 4.2.13; *Uncanistered Spent Nuclear Fuel Disposal Container System Description Document* SDD-UDC-SE-000001, CRWMS M&O 2000w, Criterion 1.2.2.1.5). These design criteria indicate, qualitatively, that breaching by impact is not a likely failure mechanism.

A preliminary quantitative analysis that translates potential postclosure ground motion to equivalent drop height is provided in *Correlation of Seismic Impact Loading to Drop Height* (CRWMS M&O 2000x). The calculations provided in the referenced input transmittal determine a maximum possible impact velocity between the waste package and ground, based on the peak vertical ground velocity and the peak vertical ground acceleration for ground motion for the 10^{-5},

10^{-6}, 10^{-7}, and 10^{-8} annual-exceedance probabilities. The results of the analysis indicated that for a median peak vertical ground acceleration of 3.2 g (i.e., the median value for the 10^{-8} annual-exceedance probability), the equivalent drop height is 2.1 m. Drop heights of 2 m in the vertical, and 2.4 m in the horizontal position are the stated preclosure-design requirements. Consequently, failure modes related to detachment from the emplacement pallet do not appear to be credible because they are addressed by preclosure-design criteria.

Impairment (increased degradation rates) can also stem from impacts and seismic vibration. Seismic vibration can lead to stress cracking and increased corrosion, with the further potential of breaching and subsequent increased seepage into waste packages. The major corrosive processes are stress-corrosion cracking in the welded lids of the waste packages and general corrosion of both the drip shield and the waste packages. Degradation of the drip shield and waste packages are *Included* in the nominal case for TSPA-SR through the WAPDEG analysis (*WAPDEG Analysis of Waste Package and Drip Shield Degradation* ANL-EBS-PA-000001, CRWMS M&O 2000y), which focuses, among other things, on the drip protection afforded to the waste packages by the drip shield. The effects are evaluated by varying the amount of moisture reaching the waste-package surface and the aperture of the openings involved. Drip-shield or waste-package damage from ground motion would be of little or no consequence unless they were located below a drip in the emplacement drift and the water were to reach the waste package. Some waste-package corrosion will occur in the humid environment under the intact drip shield, so some waste-package breaching will eventually occur even without drip-shield damage and with or without seismic-related damage to the waste package. The contribution of ground motion to degradation of the drip shield and waste package has not been specifically considered in the TSPA-SR.

In summary, the Screening Decision of *Excluded* from the TSPA-SR *(Preliminary)* has been reached based on consideration of several factors. First, preclosure damage has been shown by preliminary analysis to be of low probability. Next, the postclosure ground-motion-of-concern is infrequent (i.e., less than 10^{-5} annual-exceedance probability). Also, the likely failure mechanisms (drops and collisions) for the waste packages associated with postclosure ground motion have been addressed as preclosure-design requirements. Combined, this suggests that failure due to ground motion would be of low probability. The TSPA-SR includes waste-package degradation in the nominal case, and fuel-rod damage associated with seismic events has specifically been *Included* in the nominal case. Consequently, the additional contribution to dose due to seismic vibration damaging the waste package or drip shield would appear to be minimal. Because (1) the failure mechanisms leading to increased dose are addressed by design criteria, (2) the increase to dose due to fuel-rod-cladding failure is already *Included* in the TSPA-SR nominal case, and (3) possible degradation of the drip shield and waste packages are already addressed in the TSPA-SR in the nominal case and include uncertainties, there is a negligible potential for an increase to dose from ground-motion damage to waste packages. Therefore, "Seismic vibration causes container failure" is *Excluded* from the TSPA-SR on the basis of low consequence to dose. However, the seismic analyses for waste packages and drip shields were designated as preliminary and/or TBV by the authors of the respective sources. Consequently, the FEP is *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose.

Damage to the drip shield, and to the emplacement pallet and waste package is *Excluded* from the TSPA-SR *(Preliminary)*. Damage to the fuel-rod cladding is *Included* in the TSPA-SR.

TSPA Disposition: "Seismic vibration causes container failure" is *Excluded* from the TSPA-SR *(Preliminary)* for the drip shield, and for the emplacement pallet and waste package, as described in the Screening Argument. It is *Included* in the TSPA-SR for fuel-rod cladding.

Based on the analyses presented in *Breakage of Commercial Spent Nuclear Fuel Cladding* CAL-EBS-MD-000001 CRWMS M&O (1999d), the probability (risk) of damage to the fuel rod cladding from ground motion is on the order of 10^{-6}. The TSPA-SR addresses seismic damage to fuel-rod cladding by presuming an initial breaching of the fuel-rod cladding resulting from ground motion, followed by a progressive failure of the cladding, exposing the radionuclides and making them available for transport by seepage that enters and exits a waste package. The TSPA-SR incorporates the event probability into the nominal scenario by sampling a time of seismic cladding damage in each realization, presuming that the event follows a Poisson process with an annual frequency of 1.1×10^{-6}.

IRSR-Issues: See Attachment II

Related AMRs:

Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada ANL-CRW-GS-000003 (CRWMS M&O 2000k)

FEPs Screening of Process and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 (CRWMS M&O 2000g)

EBS Radionuclide Transport Abstraction ANL-WIS-PA-000001 (CRWMS M&O 2000h)

Breakage of Commercial Spent Nuclear Fuel Cladding by Mechanical Loading CAL-EBS-MD-000001 (CRWMS M&O 1999d).

WAPDEG Analysis of Waste Package and Drip Shield Degradation ANL-EBS-PA-000001 (CRWMS M&O 2000y)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: The TSPA-SR currently includes the effects of seismic damage as it pertains to cladding damage. However, cladding damage alone is insufficient to generate a release. The release mechanism is also dependent on degradation of the waste package and the drip shield. Degradation is being evaluated through the WAPDEG analysis, which focuses on the protection afforded to the waste package by the drip shield.

Water is not uniformly distributed in the subsurface; rather, in the ESF, it would occur in widely spaced seeps due to its preferred flow through fractures. The fractures exhibit a range of properties and spacing (see discussions in *Fault Displacement Effects on Transport in the*

Unsaturated Zone ANL-NBS-HS-000020 (CRWMS M&O 2000e). Consequently, even if drip shields or waste packages are damaged by ground motion, the damage will be of little or no importance unless it is located below a seep in the emplacement drift. Drip shields that are located beneath seeps will degrade differently than those in drier portions of the repository. Finally, waste packages under drip shields that are beneath seeps will eventually be impaired by the water. 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 (CRWMS M&O 2000i). This AMR provides the analysis for backfill and no-backfill repository designs with drifts oriented along azimuth 105. The referenced AMR also incorporates the supporting calculation (CRWMS M&O 2000j) for drifts oriented along azimuth 75 and a no-backfill design. The analyses considered the effects of thermal loading and ground motion. The FEP Screening Argument is provided in the FEP "Rockfall" (2.1.07.01.00) (see Section 6.2.17), and waste-container failure caused by rockfall (including seismic effects) in the repository drifts is *Excluded* from the TSPA-SR.

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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose.

Potential Consequence: Volcanic eruption is commonly preceded and accompanied by numerous earthquakes. Repeated vibration of a container and/or container impact with other repository elements could potentially cause the container to be damaged. Ground motion associated with seismic events has the potential to disrupt the integrity of components of the EBS or waste packages. These events could lead to decreased performance and/or to radionuclide release.

Screening Argument: Seismicity related to volcanic processes, particularly basaltic volcanoes and dike injection, was explicitly modeled in the volcanic source zones by two of the six expert teams working on the PSHA (CRWMS M&O 2000k, Table 5). Volcanic-related earthquakes were not modeled as a separate source zone by the four other PSHA expert teams because it was presumed that the low magnitude and frequency of volcanic-related seismicity were accounted for by the areal, source-zone evaluation used for the PSHA.

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). Earthquakes of moment magnitude (Mw) 5.0 and below are smaller than the maximum earthquakes assessed by the experts for their area seismic sources, and, consequently, are included in the PSHA results through the area sources.

As stated by CRWMS M&O (CRWMS M&O 2000k, Section 6.4.4), "The PSHA was computed by integrating recurrence curves for earthquakes of Mw 5.0 and greater. It is established practice that smaller earthquakes produce no damage to well-engineered structures regardless of the ground motion they generate."

In summary, seismicity associated with igneous activity is evaluated as part of the PSHA; it is, therefore, addressed in the TSPA-SR by consideration of the PSHA results. It does not, however, represent a separate mechanism for changing the properties of the host rock or for damaging the waste packages. Furthermore, the low-magnitude events associated with igneous activity do not represent a credible damage mechanism that could contribute to enhanced failure potential. Because igneous-related seismicity is not represented in the TSPA-SR by a parameter or submodel independent of the PSHA results, nor does it provide a mechanism to significantly change the dose, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

TSPA Disposition: "Seismicity associated with igneous activity" is *Excluded* from the TSPA-SR, as discussed under the Screening Argument. See Section 6.2.6 for a discussion regarding inclusion of fuel-rod-cladding damage. The probabilistic assessment of fuel-rod damage includes seismicity associated with the areal, source-zone evaluations used for the PSHA. Fuel-rod cladding damage associated with all sources of seismicity is, therefore, considered as *Included* in the TSPA-SR.

IRSR-Issues: See Attachment II

Related AMRs: *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* ANL-CRW-GS-000003 (CRWMS M&O 2000k)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: Volcanic eruption commonly is preceded and accompanied by swarms of earthquakes that indicate progressive rock-strength 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 result in ground motion at the repository. These effects have been included in the PSHA evaluations. Such earthquakes are incorporated in the PSHA as small-magnitude background earthquakes.

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 and Regulatory Basis: *Included* in the TSPA-SR—Does not satisfy a screening criterion (for direct effects related to eruptive and intrusive events and perturbation of the drifts).

Excluded from the TSPA-SR—Low consequence to dose (for indirect effects: fault-related issues, change in rock stress, rock deformation, changes in groundwater temperature).

Potential Consequence Volcanism and magmatic activity (i.e., igneous activity) could potentially alter the hydrologic characteristics of the site. This could potentially affect flow-and-transport characteristics, thereby affecting dose. The elements of the EBS and the waste packages could be damaged due to severe perturbation of the drifts, resulting in the release of radionuclides, thereby affecting dose.

Screening Argument: The TSPA Disposition below discusses the direct effects of eruptive and intrusive igneous activity that have been *Included* in the TSPA-SR. As discussed in the follow paragraphs and in more detail in related FEPs, indirect effects of eruptive and intrusive igneous activity have been *Excluded* from the TSPA-SR on the basis of low consequence to dose.

As discussed for the FEPs "Fractures" (1.2.02.02.00) and "Faults" (1.2.02.02.00), activation and sealing of faults have been *Excluded* based on low consequence to dose. The exclusions are based on the analyses of the sensitivity of radionuclide transport to changes in fracture aperture for both the fault-zone scale and the mountain-wide scale (*Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 CRWMS M&O 2000e, Sections 6.2.2.2 and 6.2.2.3). Creation of faults or movement along fractures was shown to be *Excluded* from the TSPA-SR based on the low probability of formation of new faults in intact rock due to seismic stresses (USGS 1998). It can be inferred from that analysis that rock-strength failure from an igneous event is more likely at pre-existing faults and fractures than in intact rock.

Changes in topography would be dependent on formation of surficial features. 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 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 (CRWMS M&O 2000n, 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) (CRWMS M&O 2000n, 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-SR. Changes in topography are, therefore, *Excluded* from the TSPA-SR.

Changes in rock stress and rock deformation are discussed in the FEP "Igneous activity causes changes to rock properties" (1.2.04.02.00) and are *Excluded* from the TSPA-SR based on low consequence to dose. Changes in rock stress is the approach used in the analysis for *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000e, Section 7). The UZ sensitivity analyses show that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration. 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 the FEP "Igneous activity causes changes to rock properties" (1.2.04.02.00), the volume of rock that would be affected would be limited compared to the repository area and to the volume between the repository and the critical group located 20 km away (see Section 6.2.9 of this AMR (ANL-WIS-MD-000005) for further discussion of the referenced FEP). 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).

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 *Excluded* from the TSPA-SR based on low consequence to dose. 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. 1998, pp. 5-1 and 5-2).

In summary, the indirect effects of igneous activity do not provide a mechanism to significantly affect the characteristics of the repository site. As discussed for FEPs "Fractures" (1.2.02.02.00) and for "Faults" (1.2.02.02.00), activation and sealing of faults were *Excluded* based on low consequence to dose. Creation of faults or movement along fractures were shown to be *Excluded* from the TSPA-SR based on the low probability of formation of new faults in intact rock due to seismic stresses (USGS 1998). Changes in topography would be dependent on formation of surficial features that are unlike those possible in the next 10,000 years in the Yucca Mountain region. Furthermore, the effects of changes in groundwater temperature (as reflected by hydrothermally driven mass transfer) were discussed in FEP 1.2.10.02.00, and were *Excluded* from the TSPA-SR based on low consequence to dose. Consequently, the indirect effects of igneous activity are *Excluded* based on low consequence to dose.

TSPA Disposition: The indirect effects of "Igneous activity," as described in the FEP description, are *Excluded* from the TSPA-SR, as discussed in the Screening Argument based on low consequence to dose. However, direct effects of igneous events are *Included* in the TSPA-SR, as discussed in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

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 *Included* in the TSPA-SR. The treatment of these events is discussed in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m). Additional discussion is provided in the FEP "Igneous intrusion into repository" (1.2.04.03.00).

For the eruptive/extrusive event scenario, the hypothetical eruption is presumed 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. Conduits within the repository footprint are presumed to be randomly located. It is also presumed for the referenced analysis that all intrusive events contain an eruptive phase and produce a conduit venting to land surface. The conduit erupts to land surface of the mountain, entraining the waste in the ash. 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. Inputs and parameters are specified in Section 6.1 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

It is presumed for the eruptive analysis that the waste in waste packages and the other components of the EBS that are breached by igneous activity (i.e., within the circumference of the conduit) are available to be entrained. Where conduits intersect drifts containing waste, all intersected waste packages are presumed available to be entrained in a pyroclastic eruption and to no longer provide containment of the waste. Waste material is presumed to be fragmented and to be carried upward in the rising ash cloud.

For the intrusive event, the TSPA-SR presumes that a hypothetical igneous dike intersects a section of the repository and partially or completely engulfs the intersected waste packages in magma or pyroclastic material. Regardless of the presence or absence of backfill, the waste packages within the conduit diameter, plus an additional three waste packages on either side of an intrusive dike, are presumed to provide no further protection. Other EBS components in the encompassed area are also presumed to provide no further protection. If backfill is present, damage is presumed to be limited to the area of the conduit plus a distance of three waste packages. If no backfill is present, it is presumed that the remaining waste packages in the intersected drifts are breached by an aperture of uncertain cross-section area, and that all drip shields and cladding in the intersected dikes provide no further protection.

Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

In summary, the direct effects of intrusive and extrusive events are *Included* in the TSPA-SR. Inputs and parameters are specified in Sections 6.1 and 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

IRSR-Issues: See Attachment II

Related AMRs: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m)

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

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

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

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental 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-SR includes explicit modeling of two types of igneous disruption of the repository. 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 breached by igneous intrusion. The modeling of these two igneous disruptions is described in detail in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

As specified in DOE's Interim Guidance (Dyer 1999, Section 102(j)) and proposed rule 10 CFR 63 (64 FR 8640, Section 102(j)), 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 bases for probability estimates and alternative estimates are discussed in *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, Section 6.3.1.5 and 6.3.1.6).

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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose.

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

"Igneous activity causes changes to rock properties" is *Excluded* from the TSPA-SR based on low consequence to dose.

With regard to extreme changes in hydrologic properties, sills and dikes initially intrude into the country rock as molten material and then cool. Cooling joints are formed and resulting permeabilities may be greater than, equivalent to, or less than the surrounding country rock. According to *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa), 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) state 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 rock (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 is oriented roughly north to northeast. The anisotropic transmissivity in the SZ 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, *Excluded* from the TSPA-SR based on low consequence to dose.

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 of dikes with the existing orientation of the anisotropic maximum horizontal permeability in the SZ, a dike would not form a barrier or impoundment that would have any significant effect on flow in the SZ. In the UZ, the primary direction of groundwater flow is vertically through the fractures, although some horizontal flow component exists in the matrix. Because the joints on a dike margin would be near-vertical, it would seem that the formation of a significant perched-water zone is problematic. Even if a perched-water zone were to form and then drain, there would be only a minimal impact, as explained in Section 6.2.21 of this AMR (ANL-WIS-MD-000005) for the Primary FEP "Changes in stress (due to seismic or tectonic effects) alter perched water zone" (2.2.06.03.00)).

With regard to extreme changes in mineralogy, it is possible that the thermal and geochemical influence of igneous activity could affect the rock mineralogy surrounding the igneous intrusion. However, igneous intrusions at natural-analogue sites 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 a zone less than 10 m away from the contact at Nevada Test Site natural-analogue sites (Valentine et al. 1998, pp. 5-41, 5-71, and 5-72). Valentine et al. (1998, 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 the alteration zone around dikes is limited to the immediate proximity of the dike, the changes in mineralogy are of low consequence to dose at the scale of the repository.

In summary, because each component in the FEP description has been determined by site data or natural analogues to be of minimal consequence, changes in rock properties due to igneous activity do not provide a mechanism to significantly affect dose. The subparallel orientation of dikes to transmissivity, coupled with the expected limited affected volume of the SZ, indicates that dikes, even if differing in permeability, will not significantly affect groundwater flow patterns. Because the joints on the dike margin are near-vertical, it would seem that the formation of a significant perched-water zone is problematic. Furthermore, natural-analogue studies show that alteration is limited to a zone less than 10 m away from the contact at Nevada Test Site natural-analogue sites. Therefore, the FEP is *Excluded* from the TSPA-SR based on low consequence to dose. See also "Hydrologic response to igneous activity" (1.2.10.02.00) for additional discussions.

TSPA Disposition: "Igneous activity causes changes to rock properties" is *Excluded* from the TSPA-SR, *as discussed* under the Screening Argument.

IRSR-Issues: See Attachment II

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

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: The disposition of this FEP is more fully addressed in the *YMP FEP Database* (CRWMS M&O 2000c, Appendix D).

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 and Regulatory Basis: *Included* in the TSPA-SR—Does not satisfy a screening criterion.

Potential Consequence: Igneous intrusion into the repository (i.e., igneous activity) could potentially alter the hydrologic characteristics of the site and, thereby,

thereby, affect flow-and-transport characteristics and dose. The elements of the EBS and the waste packages could be damaged due to severe perturbation of the drifts, thereby resulting in the release of radionuclides and affecting dose.

Screening Argument: "Igneous intrusion into repository" is *Included* in the TSPA-SR, as described under the TSPA Disposition.

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

For the intrusive event modeled in the TSPA-SR, a hypothetical igneous dike intersects a section of the repository and partially or completely engulfs the intersected waste packages in magma or pyroclastic material. Regardless of the presence or absence of backfill, the waste packages within the conduit diameter, plus an additional three waste packages on either side of an intrusive dike, are presumed to provide no further protection. The TSPA-SR presumes that other EBS components in the encompassed area provide no further protection. If backfill is present, damage is presumed to be limited to the area of the conduit plus a distance of three waste packages. If no backfill is present, it is presumed that the remaining waste packages in the intersected drifts are breached by an aperture of uncertain cross-section area, and that all drip shields and cladding in the intersected dikes are presumed to provide no further protection.

Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. Dissolution of waste in basaltic melt is not considered explicitly but is conservatively bounded by presuming in the TSPA-SR that waste is exposed directly to groundwater without any protection from the surrounding basalt. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

In summary, intrusive events are *Included* in the TSPA-SR, and inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

IRSR-Issues: See Attachment II

Related AMRs: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m)

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

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

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

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: The TSPA-SR includes explicit modeling of the consequences of igneous disruption of the repository.

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 initially a dike (a vertical tabular body) rather than a sill (a horizontal tabular body), although horizontal flow into the drifts is considered. This redefinition is based on the results of *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa, 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 more likely than 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 (which has a 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 2000aa, Figures 2 and 3).

As specified in DOE's Interim Guidance (Dyer 1999, Section 102(j)) and proposed rule 10 CFR 63 (64 FR 8640, Section 102(j)), 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 C*haracterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, Section 6.3.1.5 and 6.3.1.6).

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 and Regulatory Basis: *Included* in the TSPA-SR—Does not satisfy a screening criterion.

Potential Consequence: Magma could interact with the elements of the EBS and the waste packages could be impaired due to severe perturbations in the drifts, thereby, resulting in breaching of the waste packages. This has the potential to result in the release of radionuclides, thereby affecting dose.

Screening Argument: "Magma interacts with waste" is *Included* in the TSPA-SR, 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-SR, as described in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m, Section 5).

For the intrusive event, the TSPA-SR presumes that a hypothetical igneous dike intersects a section of the repository and partially or completely engulfs the intersected waste packages in magma or pyroclastic materials. Regardless of the presence or absence of backfill, the waste packages within the conduit diameter, plus an additional three waste packages on either side of an intrusive dike, are presumed to provide no further protection. The TSPA-SR also presumes that other EBS components in the encompassed area provide no further protection. If backfill is present, damage is presumed to be limited to the area of the conduit plus a distance of three waste packages. If no backfill is present, it is presumed that the remaining waste packages in the intersected drifts are breached by an aperture of uncertain cross-section area, and that all drip shields and cladding in the intersected dikes are presumed to provide no further protection.

The TSPA-SR does 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. Attack by magmatic volatiles and mechanical degradation could further damage the waste packages but would not result in conditions more extreme than presuming that the waste packages within the conduit diameter (plus three waste packages to either side) provide no further protection. The TSPA-SR presumption of damage to remaining waste packages in the drift for the no-backfill scenario is based on thermal calculations that indicate that deformation of the lid at the end of a waste package at high temperatures (1100 degrees C) and high pressure (7.5 Mpa) may cause failure of the welds between the waste packages and the lid (*Waste Package Behavior in Magma.* CAL-EBS-ME-000002 CRWMS M&O 1999e). Because this type of failure would not remove waste from the waste package shell, breaching of the waste packages by an aperture is a reasonable approach.

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 *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z, Section 6.5).

Eruptive processes are addressed in, "Basaltic cinder cone erupts through the repository" (1.2.04.06.00).

In summary, magma interactions with waste are in *Included* in the TSPA-SR, and inputs and parameters are specified in Sections 6.1 and 6.2 of *Igneous Consequence Modeling for the TSPA-*

SR ANL-WIS-MD-000017 (CRWMS M&O 2000m) and in *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z, Section 6.5).

IRSR-Issues: See Attachment II

Related AMRs:

Igneous Consequence Modeling for the TSPA-SR
ANL-WIS-MD-000017 (CRWMS M&O 2000m)

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

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

Waste Package Behavior in Magma
CAL-EBS-ME-000002 (CRWMS M&O 1999e)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: All waste types are included in the analysis in the same way that they are included in the TSPA-SR analyses of the nominal-case 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 could slow or prevent groundwater from reaching the waste. The transport of the waste is dependent on the solubility limits of the waste and the availability of groundwater. Doses to the critical group from this event are calculated in the TSPA.

Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. Dissolution of waste in basaltic melt is not considered explicitly but is conservatively bounded by presuming in the TSPA-SR that waste is exposed directly to groundwater without any protection from the surrounding basalt. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

As specified in DOE's Interim Guidance (Dyer 1999, Section 102(j)) and proposed rule 10 CFR 63 (64 FR 8640, Section 102(j)), 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 bases for probability estimates and alternative estimates are discussed in *Characterize Framework for*

Igneous Activity at Yucca Mountain, Nevada ANL-MGR-GS-000001 (CRWMS M&O 2000n, Section 6.3.1.5 and 6.3.1.6).

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 land surface.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose (for transport in liquid magma and other types of magmatic transport).

Included in the TSPA-SR—Does not satisfy a screening criterion (for non-magmatic transport through an eruptive event).

Potential Consequence: Waste is entrained, dissolved, or volatilized in magma that either remains in the subsurface and is exposed to groundwater, or reaches land surface and is then transported.

Screening Argument: The potential consequence involves two elements: (1) entrainment, dissolution, or volatilization of the waste, and (2) transport.

Entrainment, dissolution, or volatilization occur as a result of intrusion of the repository. For the intrusive event, the TSPA-SR presumes that a hypothetical igneous dike intersects a section of the repository and partially or completely engulfs the intersected waste packages in magma or pyroclastic material. Regardless of the presence or absence of backfill, the waste packages within the conduit diameter, plus an additional three waste packages on either side of an intrusive dike, are presumed to provide no further protection. The TSPA-SR presumes that other EBS components in the encompassed area provide no further protection. If backfill is present, damage to waste packages is presumed to be limited to the area of the conduit plus a distance of three waste packages. If no backfill is present, it is presumed that the remaining waste packages in the intersected drifts are breached by an aperture of uncertain cross-section area, and that all drip shields and cladding in the intersected dikes are presumed to provide no further protection.

Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

Dissolution of waste in basaltic melt is not considered explicitly. However, the TSPA-SR presumption that waste packages provide no further protection or only partial protection from groundwater entering the drifts effectively bounds the consequence of waste dissolved in the basalt being transported in groundwater. Similarly, volatilized and redeposited radionuclides will not be any more accessible to groundwater transport than the solid waste material exposed in damaged waste packages resulting from an intrusive event, as described above. Transportation of any volatilized radionuclides over the distances for which temperatures will remain high enough will have no additional effect.

With regard to the surface transport of waste, the critical group is specified by guidance to be located at 20 km from the repository. In contrast, the Quaternary-age features typically consist of a single main scoria cone surrounded by a small field of *aa* basalts (approximately 1 km in extent) (CRWMS M&O 2000n, Section 6.2). 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 (CRWMS M&O 2000n, Section 6.2 and Table 4). Consequently, it is not credible to presume 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 not credible.

Because transport in liquid magma is not a credible event and related effects (such as dissolution in basalt and volatilization) are bounded by the TSPA-SR approach, magmatic transport does not provide a mechanism to significantly change the dose. Therefore, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

TSPA Disposition: "Magmatic transport of waste" is *Excluded* from the TSPA-SR, as discussed in the Screening Argument. Transport via an eruptive event and through pyroclastic eruption is *Included* in the TSPA-SR and is addressed in the FEPs "Ashfall" (1.2.04.07.00) and "Basaltic cinder cone erupts through the repository" (1.2.04.06.00). Magma interaction with waste is *Included* in the TSPA-SR, as described for FEP 1.2.04.04.00.

IRSR-Issues: See Attachment II

Related AMRs: *Igneous Consequence Modeling for the TSPA-SR*
ANL-WIS-MD-000017 (CRWMS M&O 2000m)

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

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

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

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: As specified in DOE's Interim Guidance (Dyer 1999, Section 102(j)) and proposed rule 10 CFR 63 (64 FR 8640, Section 102(j)), 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 bases for probability estimates and alternative estimates are discussed in *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, Section 6.3.1.5 and 6.3.1.6).

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 and Regulatory Basis: *Included* in the TSPA-SR—Does not satisfy a screening criterion.

Potential Consequence: A basaltic cone is not erupted in the same sense as volcanic ash or lava but is a secondary result of the eruptive accumulation of ash and lava. The conduit(s) supplying the vent(s) or cone could pass through the repository. Magma from the conduits could interact with the elements of the EBS, and the waste packages could be impaired or breached due to potentially severe perturbations in the drifts, thereby resulting in the release of radionuclides. The radionuclides would then be transported to land surface and into the lower atmosphere during the pyroclastic phase of eruption and transported toward the critical group.

Screening Argument: "Basaltic cinder cone erupts through the repository" (1.2.04.06.00) *is Included*, as described in the TSPA Disposition.

TSPA Disposition: "Basaltic cinder cone erupts through the repository" is *Included* in the TSPA-SR and is addressed through the modeling of an eruptive event. Consequences of an igneous intrusion through the repository and a resulting eruptive event are explicitly *Included* in the TSPA-SR, and appropriately weighted by the probability of occurrence of the events. The TSPA-SR includes explicit modeling of two types of igneous disruptions of the repository. These include (1) the release of radionuclides into the groundwater from waste packages breached by igneous intrusion, and (2) direct releases of contaminated ash during volcanic eruptions, with contaminated ash resulting from conduits intersecting the repository. The modeling of these two igneous disruptions is described in detail in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

The distributions used for modeling dike characteristics and for the number of eruptive cones and centers is presented in *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, Section 6.5.3.1). Of particular note, the conditional distribution for the number of eruptive centers inherently addresses the consequences of the Secondary FEP "Vent jump" (1.2.04.06.01). Properties of the basaltic eruption are described in *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z) 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 "Vent erosion" (1.2.04.06.02).

For the eruptive/extrusive event scenario, the TSPA-SR presumes that a hypothetical eruption occurs 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. Conduits within the repository footprint are presumed by the TSPA-SR to be randomly located. It is also presumed for the referenced analysis that all intrusive events contain an eruptive phase and produce a conduit venting to land surface. The conduit erupts to land surface, entraining the waste in the ash. 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 modeling are then used to calculate dose to the critical group for the TSPA. Inputs and parameters are specified in Section 6.1 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

It is presumed for the eruptive analysis modeled in the TSPA-SR that waste in waste packages, as well as other components of the EBS that are breached by igneous activity (i.e., within the circumference of the conduit), are available to be entrained. Where conduits intersect drifts, intersected waste packages are presumed to no longer provide containment of the waste. Waste material is presumed to be fragmented, entrained in a pyroclastic eruption, and carried upward in the rising ash cloud.

In summary, "Basaltic cinder cone erupts through the repository (1.2.04.06.00)" is *Included* in the TSPA-SR. Inputs and parameters are specified in Section 6.1 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

IRSR-Issues: See Attachment II

Related AMRs:

Igneous Consequence Modeling for the TSPA-SR
ANL-WIS-MD-000017 (CRWMS M&O 2000m)

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

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

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

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: As specified in DOE's Interim Guidance (Dyer 1999, Section 102(j)) and proposed rule 10 CFR 63 (64 FR 8640, Section 102(j)), 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 bases for probability estimates and alternative estimates are discussed in *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, Section 6.3.1.5 and 6.3.1.6).

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 and Regulatory Basis: *Included* in the TSPA-SR—Does not satisfy a screening criterion (for ash cloud and surface deposition).

Excluded from the TSPA-SR—Low consequence to dose (for pyroclastic flow).

Potential Consequence: Magma could interact with the elements of the EBS, and the waste packages could be breached due to severe perturbations in the drifts, thereby, resulting in the release of radionuclides. The radionuclides would then be transported to land surface and into the lower atmosphere during the pyroclastic phase of eruption and transported toward and deposited in the vicinity of the critical group.

Pyroclastic flows (as opposed to ashflows or pyroclastic eruptions) are *Excluded* from the TSPA-SR 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 (CRWMS M&O 2000n, Section 6.2 and Table 4). Because the proposed mechanism is not credible due to the distances and volumes involved, this portion of the FEP will not significantly affect dose. Therefore, it is *Excluded* from the TSPA-SR based on low consequence to dose.

Ashfall is *Included* in the TSPA-SR, 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-SR model for the Igneous Activity Disruptive Scenario, as described in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m, Section 6.1).

For the eruptive/extrusive event scenario, the TSPA-SR presumes that a hypothetical eruption occurs 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. Conduits within the repository footprint are presumed in the TSPA-SR to be randomly located. It is also presumed for the referenced analysis that all intrusive events contain an eruptive phase and produce a conduit venting to land surface. The conduit erupts to land surface of the mountain, entraining the waste in the ash. 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. Inputs and parameters are specified in Section 6.1 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

It is presumed for the eruptive analysis in the TSPA-SR that waste in waste packages, as wells as other components of the EBS that are breached by igneous activity (i.e., within the circumference of the conduit), are available to be entrained. Where conduits intersect drifts, intersected waste packages are presumed to no longer provide containment of the waste. Waste material is presumed to be fragmented, entrained in a pyroclastic eruption, and carried upward in the rising ash cloud.

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-SR through sampling from cumulative distribution functions based on available information (see *Igneous Consequence Modeling for the TSPA-SR Analysis* ANL-WIS-MD-000017: CRWMS M&O 2000m, Section 6.1).

In summary, the TSPA-SR 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 2000z) and are based on the observed characteristics of past basaltic eruptions in the Yucca Mountain region and other analogous eruptions.

IRSR-Issues: See Attachment II

Related AMRs:

Igneous Consequence Modeling for the TSPA-SR ANL-WIS-MD-000017 (CRWMS M&O 2000m)

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

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

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

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: As specified in DOE's Interim Guidance (Dyer 1999, Section 102(j)) and proposed rule 10 CFR 63 (64 FR 8640, Section 102(j)), 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 bases for probability estimates and alternative estimates are discussed in *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, Section 6.3.1.5 and 6.3.1.6).

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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose *(Preliminary).*

Potential Consequence: Seismic activity is the result of fault slip, and both processes can cause changes in rock stresses. The change in the state of stress has the potential to affect the groundwater flow and the transport properties of the UZ and or SZ. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS or waste packages, leading to a release of radionuclides.

Screening Argument: This FEP includes the effects of seismic activity on UZ and SZ 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). This FEP is more fully addressed in *Features, Events and Processes in the UZ Flow and Transport (*CRWMS M&O 2000q, Section 6.2.6). Fault movement effects are also addressed in the Primary FEPs "Fractures" (1.2.02.02.00) (see Section 6.2.3), and "Faulting" (1.2.02.03.00) (see Section 6.2.4).

Regardless of its origin, seismic activity in the UZ would either be transient in nature or result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The effects of changes to fracture systems due to geologic effects on mountain-scale flow and radionuclide transport have been investigated using a sensitivity approach in *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000e). The effects of changes in fracture apertures are examined because several fracture properties (permeability, capillary pressure, and porosity) are functions of fracture aperture. The results indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration (CRWMS M&O 2000e, Section 7). However, the conclusions in CRWMS M&O (2000e) were designated as TBV. Because radionuclide transport is not significantly affected, dose is not affected. Therefore, seismic effects on the UZ are *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose.

Earthquakes effect changes in groundwater levels, often at distances far removed from the epicenter. Such changes have the potential to alter groundwater-flow directions. The mechanism for changing surface-water-flow directions is not readily apparent, unless it is related to the relocation of recharge and discharge structures, which is related to changes in water levels. The mechanisms for affecting water chemistry and temperature are also undefined but are presumed to be linked to a change in groundwater levels. However, such water-level 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 m within an hour of a simulated seismic event. The simulated system returns to steady-state conditions within six months. Gauthier et al. (1996, pp. 163-164) conclude 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). Because water-table changes do not reach the repository level and are transitory in nature, groundwater flow and radionuclide transport are not significantly affected. The hydrologic response to seismic activity, therefore, does not provide a mechanism to significantly affect dose. Therefore, the FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

In summary, the effects of seismic activity (regardless of origin) in the UZ would either be transient in nature or result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The effects of changes to fracture systems 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 2000e) and indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration (CRWMS M&O 2000e, Section 7). Therefore, the hydrologic response to seismic activity is of low consequence to dose and is *Excluded* from the TSPA-SR.

TSPA Disposition: "Hydrologic response to seismic activity" is *Excluded* from the TSPA-SR *(Preliminary)*, as described under the Screening Argument.

IRSR-Issues: See Attachment II

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

Features, Events, and Processes in SZ Flow and Transport ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: See Screening Argument

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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose.

Potential Consequence: 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. Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and dose. The elements of the EBS and the waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and to premature failures, thereby resulting in the release of radionuclides and consequently affecting dose.

Screening Argument: The effects of igneous activity on the UZ are discussed more fully in *Features, Events and Processes in UZ Flow and Transport* (CRWMS M&O 2000q, Sections 6.7.7). Formation of perched water in the UZ above the repository and subsequent focused flow due to seismic activity is addressed in the TSPA-SR indirectly through the seepage model abstraction. This mechanism would be analogous to the effects of igneous activity (i.e., focused flow due to dikes). Drainage of perched-water zones below the repository was *Excluded* based on low consequence to dose because the minimal volume of water involved would not affect dose from the saturated zone.

According to *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa), 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) state that the Paiute Ridge dike on the Nevada Test Site.

> . . . 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 rock (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 increased permeability is parallel with the dike margins and will be oriented roughly north to northeast. The anisotropic transmissivity in the SZ observed in the Yucca Mountain region indicates 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 or water levels. Because there would be no significant change to the flow system, hydrologic response to igneous activity does not provide a mechanism for significantly changing dose. Therefore, changes in permeability and flow directions due to igneous activity are of minimal consequence with respect to repository performance.

Because of the parallel orientation of dikes with the existing orientation of the anisotropic maximum horizontal permeability in the SZ, it is problematic that a dike would form a barrier or impoundment in the SZ. Furthermore, the TSPA-VA evaluation for disruptive events (CRWMS M&O 1998c, 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. Because there would be no significant change to the flow system, dike intrusion does not provide a mechanism for significantly changing dose. Changes in permeability and flow systems are, therefore, *Excluded* from the TSPA-SR based on low consequence to dose.

Based on the study of natural-analogue sites, Valentine et al. (1998, p. 5-1 and 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 zeolitized tuffs (Valentine et al. 1998, p. 5-42). The analogue studies show that alteration is quite limited, typically only found within 5 to 10 m of intrusions (Valentine et al. 1998, 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 and the consequent change of rock properties around the intrusion, the effect of alteration is minimal, and alteration does not provide a mechanism to significantly change the dose. Therefore, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

Valentine et al. (1998, p 5-86) have also considered the effects of hydrothermal systems (the heating up of groundwater and rock) resulting from igneous intrusions. Findings from the Paiute Ridge analogue site indicate that "the occurrence of clinoptilolite and opal also suggests that thermal transfer into the adjacent country rock was minimal" (Valentine et al. 1998, p. 5-57). Findings from the Grants Ridge site suggest the absence of a hydrothermal system, except for localized recrystallization of volcanic glass within the contact zone (Valentine et al. 1998, 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 *Excluded* from the TSPA-SR based on low consequence to dose 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. (1998, 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 than 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 *Excluded* from the TSPA-SR based on low consequence to dose.

In summary, the parallel orientation of dikes and the direction of maximum 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 from the host rock, will not significantly affect groundwater-flow patterns or water levels. Because there would be no significant change to the flow system, hydrologic response to igneous activity does not provide a mechanism for significantly changing dose. Given the limited area of alteration and the consequent change of rock properties around the intrusion, the effect of alteration would be minimal, and alteration would not provide a mechanism to significantly change the dose. Furthermore, the development of hydrothermal systems from igneous activity is *Excluded* from the TSPA-SR based on low consequence to dose due to their limited size respective to the repository footprint. Consequently, "Hydrologic response to igneous activity" is *Excluded* from the TSPA-SR based on low consequence to dose.

TSPA Disposition: "Hydrologic response to igneous activity" is *Excluded* from the TSPA-SR, as described in the Screening Argument

IRSR-Issues: See Attachment II

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

Features, Events, and Processes in SZ Flow and Transport ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: Another concern is the possibility that a large steam explosion could occur, such that a large phreatic or a phreatomagmatic crater (maar) might form. 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, 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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose *(Preliminary).*

Potential Consequence: With time and changes in the state of stress in the repository block due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading, the rock mass surrounding the emplacement drifts will deteriorate. Large blocks (e.g., key blocks) may form at the intersection of three or more planes of structural discontinuities such as joints and fractures. A triggering event may cause movement or fall of the key block onto the drip shield and/or waste packages. The drip shield and/or waste package may be breached and radionuclides made available for transport. Water may flow through the breach to transport the radionuclides from the repository.

Screening Argument: The potential consequence requires that two factors be realized: (1) that rockfall occurs, and (2) that the block of rock is of sufficient size to cause a breach in the drip shield and/or waste package.

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 (CRWMS M&O 2000i) for the design including backfill (CRWMS M&0 1999a, EDA II, pp. 4-16 and 4-17) and also for the no-backfill design. (CRWMS M&O 2000a). This analysis presumes drift orientations along azimuth 105 for backfill and no-backfill cases; considers static, thermal, and seismic conditions; and analyzes for drift azimuths varying every 15 degrees for static conditions. The referenced AMR also incorporates the results of *Supporting Rock Fall Calculation for Drift Degradation: Drift Reorientation with No Backfill CAL-EBS-MD-000010* (CRWMS M&O 2000j) that has been performed for a no-backfill design with drifts oriented along azimuth 75. The current repository design (CRWMS M&O 2000b) includes a drip shield and drifts oriented along azimuth 252 (or a corresponding azimuth 72). (See Assumption 5.3 of this AMR (ANL-WIS-MD-000005)).

An analysis of the potential for rockfall for the design with no backfill and reoriented drifts from CRWMS M&O (2000b) is presented in CRWMS M&O (2000j). The analysis activities for CRWMS M&O (2000j) involved using analytical methods, including DRKBA, a numerical code, and UNWEDGE, a software program for the calculation of block shapes. The analysis provides calculations and statistical analyses to determine the expected quantities, locations, size distributions, and frequencies of rockfall for the repository emplacement drifts.

The input data for CRWMS M&O (2000j) included developed geometrical data for joints based on qualified field-mapping data from the ESF. Joint sets were identified based on clustering data from joint normal vectors plotted on stereonets. In addition to the primary joint sets, a random joint set was simulated to account for any joint that is present in the rock mass but not accounted for in the data for the primary joint sets. The analysis presumed no ground support and is, therefore, conservative.

The frictional properties of joints were modified to determine the effects of both thermal and time-dependent degradation, as well as for seismic loading conditions on key-block development. Thermal effects were evaluated for multiple time periods including static conditions (0 years), 200 years, 2,000 years and 10,000 years. Seismic evaluation included evaluation at three preclosure seismic-design levels corresponding to 0.14 g (a 1,000-year event), 0.30 g (a 5,000-year event), and 0.43 g (a 10,000-year event) (CRWMS 2000i, p. 22). See Assumptions 5.4 and 5.5 of this AMR (ANL-WIS-MD-000005)) for applicability for postclosure requirements. The results indicate that preclosure seismic, time-dependent, and thermal effects have a relatively minor influence on rockfall probabilities.

Because the joint data vary by lithology, and the differences in joint data by lithology are captured in the analyses, the rockfall calculations must also account for the length of drift in each lithologic unit. The various designs for the repository (CRWMS M&O 1999a and 2000b) include emplacements drifts located in three lithologic units: 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). The analysis from CRWMS M&0 (2000j) suggests that fewer than 15 key blocks larger than the design rock block (6 MT) will be present in the repository for any of the given conditions (time-dependent, thermal, or seismic) considered in the analysis. These results are based on an azimuth 75 drift orientation and a design rock block of 6 MT.

Table 3 summarizes the results of CRWMS M&O (2000j) for drift azimuth 75 with no backfill.

Table 3. Summary Results of Rockfall Analysis for No-Backfill Design and Reoriented Drifts

Lithologic Unit	Result	Static	Static + Seismic Level 3	Static + Thermal and Time Dependent (10,000 years)
Tptpmn	Total number of blocks / Blocks per km	138 / 28	154 / 32	(144) / 30
	Percentage of blocks at or less than design block size	99.3	96.8	97
	Percentage of blocks greater than design block size	0.7	3.2	3
	Maximum block size (MT)	12.04	33.75	33.75
Tptpll	Total number of blocks / Blocks per km	21 / 2	21 / 2	(21) / 2
	Percentage of blocks at or less than design block size	100	100	100
	Percentage of blocks greater than design block size	0	0	0
	Maximum block size (MT)	3.11	3.11	3.11
Tptpln	Total number of blocks / Blocks per km	54 / 6	67 / 7	(67) / 7
	Percentage of blocks at or less than design block size	90.7	85.1	89
	Percentage of blocks greater than design block size	9.3	14.9	11
	Maximum block size (MT)	25.56	37.16	37.16

Notes:

1. Data taken from Tables 12 through 16, Tables 18 through 21, and Tables IV-1 through IV-4 of CRWMS M&O (2000j)
2. Data for percentage of block size for Static + Thermal and Time Dependent are interpreted from Tables 18 through 21 and Figures 6, 7, and 8 of CRWMS M&0 (2000j)
3. Total number of blocks for Static + Thermal and Time-Dependent are in parenthesis "( )" and were inferred from CRWMS M&O 2000(i) based on proportionality of total number of blocks to blocks per km for other conditions.

As the table indicates, for the design with no backfill and reoriented drifts (the design specified in CRWMS M&O 2000b), the predicted numbers of key blocks per unit length of drift are generally low.

Based on the LADS EDA II design (CRWMS M&O 1999a), which included backfill and a different drift orientation than for the current design, the predicted numbers of key blocks per unit length of drift were also generally low, with a maximum of 44 blocks per kilometer in the Tptpmn lithologic unit (*Drift Degradation Analysis* ANL-EBS-MD-000027, CRWMS M&O 2000i, p. 57). For the Tptpll unit, the number of key blocks predicted was minimal (4 blocks per kilometer). The emplacement-drift openings for the backfill design are predominantly located in the Tptpll.

Based on the results of CRWMS M&O (2000j), the maximum key-block size expected is 37 MT. The impact of rockfall on the drip shield is discussed in *Rock Fall on Drip Shield,* CAL-EDS-ME-000001 (CRWMS M&O 2000t). The calculation indicates that no cracks develop in the drip shield (i.e., no breaching) due to the dynamic impact of a rockfall on the drip shield for an effective rock mass of 10 MT over a 3-m length of drip shield, or up to a key-block size of 52 MT. This calculation presumes that the rock block does not fail at impact and is also based on the material characteristics provided in Section 5 of the calculation. If block-size increases due to increased ground motion associated with lower probability postclosure seismic activity, then the increase in size would be principally in length rather than apex height, and the effective rock mass would not increase to over 10 MT. The presence of the drip shield (see Assumptions 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005)), therefore, precludes rockfall as a credible scenario contributing to direct waste-package failure (i.e., breaching). Stress-corrosion cracking in the drip shield may, however, result from residual stresses depending on the size of the rock (See Section 6.2.6 of this AMR (ANL-WIS-MD-000005), "Seismic vibration causes container failure" (1.2.03.02.00), for a discussion of degradation of the drip shield).

The occurrence of large key-block rockfall is relatively infrequent, and the largest estimated key block is smaller than that used in the analysis. The analysis *Rock Fall on Drip Shield,* CAL-EDS-ME-000001 (CRWMS M&O 2000t) indicates that no breaching of the drip shield occurs due to rockfall, even with the larger block sizes associated with seismic and thermal loading. Even if the drip shield were to be ruptured, the force of the impact would have been absorbed by the drip shield and would not be transferred completely to the waste package. The waste package itself is also being designed to withstand rockfall events.

In summary, because the maximum key-block size is insufficient to breach the drip shield, rockfall does not provide a mechanism to increase radionuclide release. If no radionuclide release occurs due to rockfall, there would be no significant change to dose. However, both the *Drift Degradation Analysis* ANL-EBS-MD-000027 (CRWMS M&O 2000i) and *Supporting Rock Fall Calculation for Drift Degradation: Drift Reorientation with No Backfill CAL-EBS-MD-000010* (CRWMS M&O 2000j) are associated with data that has been designated as TBV. Consequently, the FEP is *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose. The secondary FEPs, which include the impact of rockbursts on waste packages (see Attachment II), are also *Excluded* from the TSPA-SR.

TSPA Disposition:	Rockfall (large block) is *Excluded* from the TSPA-SR *(Preliminary)*, as described under the Screening Argument.
IRSR-Issues:	See Attachment II
Related AMRs:	*Drift Degradation Analysis* ANL-EBS-MD-000027 (CRWMS M&O 2000i) *Supporting Rock Fall Calculation for Drift Degradation: Drift Reorientation with No Backfill* *CAL-EBS-MD-000010* (CRWMS M&O 2000j) *Rockfall on Drip Shield* CAL-EDS-ME-000001 (CRWMS M&O 2000t)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: Due to the limitation of DRKBA, thermal and 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 thermal and seismic effects. The reduced joint-strength parameters (cohesion and friction angle) are provided in *Drift Degradation Analysis* ANL-EBS-MD-000027 (CRWMS M&O 2000i, p. 38). 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: CRWMS M&O 2000i, p. 104). These same adjustments in parameters were used for CRWMS M&O (2000j).

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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose *(Preliminary).*

Potential Consequence: With time and changes in the state of stress in the repository due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading, the rock mass surrounding the emplacement drifts will deteriorate. Key blocks may form at the intersection of three or more planes of structural discontinuity such as joints and fractures. A triggering event may cause movement or fall of small key blocks, and the drift collapse could affect stability of the EBS and waste packages, as well as leading to rubble accumulating in parts of the drift. The presence of the rubble may alter thermal characteristics in the EBS and affect component performance, and/or water may flow through tears or ruptures to transport the radionuclides from the repository. This FEP is focused on the effects of small key blocks and/or accumulation of rubble.

Screening Argument: The various repository designs (CRWMS M&O 1999a, p. 4-16 and 4-17 and CRWMS M&O 2000b) include a drip shield. Rockfall data for both backfill and no-backfill designs are addressed in *Drift Degradation Analysis* (CRWMS M&O 2000i) and *Supporting Rock Fall Calculation for Drift Degradation: Drift Reorientation with No Backfill CAL-EBS-MD-000010* (CRWMS M&O 2000j). A calculation of the potential for rockfall to cause damage to the drip shield is presented in *Rock Fall on Drip Shield,* CAL-EDS-ME-000001 (CRWMS M&O 2000t) and is more fully discussed in Section 6.2.17 of this AMR (ANL-WIS-MD-000005) for the Primary FEP "Rockfall (large block)" (2.1.07.01.00). The analysis indicates that no cracks develop in the drip shield due to the dynamic impact of a rock on the drip shield for an effective rock mass of up to 10 MT over a 3-m length of drip shield. Breaching of the drip shield by small key-block rockfall is, therefore, not a credible event (see Assumptions 5.2 and 5.3 of this AMR (ANL-WIS-MD-000005)).

The analysis in CRWMS M&O (2000j) provides the number and size distribution of key blocks that are likely to occur. As shown in Table 3 in Section 6.2.17 of this AMR (ANL-WIS-MD-000005), rockfall of any type is an infrequent event. The maximum density of rockfalls is 32 per km of drift in a 10,000 year period, and 75 percent of the key blocks are 0.24 m^3 or less in volume (CRWMS M&O 2000j, Tables 12 and 15). In some instances the key-block density is as little as 2 per km. CRWMS M&O (2000j) includes consideration of preclosure seismic-design levels (see Assumptions 5.4 and 5.5 of this AMR (ANL-WIS-MD-000005). The results of the analysis presented in CRWMS M&O (2000j) indicate that preclosure seismic, time-dependent, and thermal effects have a relatively minor influence on rockfall probabilities. Consequently, concerns that rubble buildup will lead to stability issues and/or thermal buildup are not credible.

In summary, the presence of the drip shield precludes "Mechanical degradation or collapse of drift" as a credible scenario contributing to direct waste-package breaching or damage. Because no damage to the waste packages occurs from the degradation or collapse of the drift, such an event does not provide a mechanism for a radionuclide release, and, therefore, there would be no increase or significant change in dose. However, both the *Drift Degradation Analysis* ANL-EBS-MD-000027 (CRWMS M&O 2000i) and *Supporting Rock Fall Calculation for Drift Degradation: Drift Reorientation with No Backfill* CAL-EBS-MD-000010 (CRWMS M&O 2000j) are associated with data that have been designated as TBV. Consequently, the FEP is *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose.

TSPA Disposition:	Mechanical degradation or collapse of drift is *Excluded* from the TSPA-SR, as described under the Screening Argument
IRSR-Issues:	See Attachment II
Related AMRs:	*Drift Degradation Analysis* ANL-EBS-MD-00002 (CRWMS M&O 2000i) *Supporting Rock Fall Calculation for Drift Degradation: Drift Reorientation with No Backfill* *CAL-EBS-MD-000010* (CRWMS M&O 2000j) *Rockfall on Drip Shield* CAL-EDS-ME-000001 (CRWMS M&O 2000t)
Treatment of Secondary FEPs:	See Table 4 and Attachment II
Supplemental Discussion:	See discussion in Section 6.2.17 of this AMR (ANL-WIS-MD-000005) for FEP "Rockfall (large block)" (2.1.07.01.00).

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 to result in strains that affect flow properties in rock outside the excavation-disturbed zone.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose.

Potential Consequence: Changes in stress due to all causes have the potential to result in strains that affect the groundwater flow-and-transport properties leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS or waste packages, leading to a release of radionuclides

Screening Argument: Changes in stress may result in changes to existing hydrologic characteristics of fracturing. The following screening argument considers the UZ, the SZ, and the potential for the reactivation of existing fractures and creation of new fractures. Available analysis for the UZ, as discussed below, considers the potential effects on the rock matrix and fractures. The analyses for the SZ, also discussed below, briefly discuss inclusion of uncertainties in the data distribution, which minimizes the significance of future changes in the fracture properties.

The effects of changes to fracture systems in the UZ 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 2000e). Because this analysis is a key support document for the screening decision for this FEP, some details regarding the analysis are further discussed.

The UZ sensitivity analyses are performed with the nominal UZ three-dimensional flow model and using several conservatisms that together provide bounding cases for determining whether changes in fractures will significantly impact repository performance. The analyses are performed using a dual-permeability, active-fracture flow model, and are based on the changing of fracture apertures that could be the result of strain conditions or other factors. Given a change in fracture aperture, other hydrologic properties of fractures (permeability, capillary pressure, and porosity) are estimated through the use of theoretical models. The sensitivity of fracture aperture to mechanical strain is due to the small porosity of the fracture continuum. The matrix on the other hand, has much greater porosity than the fractures in general, and its properties are not expected to be as sensitive to mechanical strain: the fracture porosity is much less than the matrix porosity at Yucca Mountain (CRWMS M&O 2000e, Assumption 5.2). The UZ sensitivity analyses (CRWMS M&O 2000e) indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration (CRWMS M&O 2000e, Section 7).

The results of the sensitivity study are used to support multiple FEPs that examine potential effects due to changes in stress conditions (see Sections 6.2.15, 6.2.19, and 6.2.20 of this AMR (ANL-WIS-MD-000005). Because the analysis is based on the net changes in fracture apertures, the proximal cause of that change (e.g., faulting, seismicity, tectonism, thermal loading) is insignificant, as long as the expected change in apertures falls within the range of the fracture apertures examined in the analysis. The sensitivity study considers a maximum increase of 10 times the existing fracture aperture and a decrease of 0.2 times the existing fracture apertures.

The sensitivity analysis includes two bounding cases: (1) the change in fracture properties occurs over the entire UZ domain (fault zones and fractured rock), or (2) a more realistic case: the effect of fault displacement is limited to fracture-property changes in fault zones. These are modeling cases chosen to bound a presumed range of fracture-aperture changes resulting from fault movement. There are no direct observations for Yucca Mountain that relate stress caused by fault displacement to strain and resultant changes in fracture aperture. The bounding cases are used to simulate a response beyond that of the expected geologic response.

Two conservatisms are present in the sensitivity analysis. The first conservatism is that the increase in fracture aperture used in the analysis is based on a presumed fault displacement that is greater than those that are observed along the block-bounding faults or, based on the PSHA, likely to occur. This conservatism applies to both of the bounding cases used for the analysis. The second conservatism involves the distribution of strain over the entire UZ domain in response to fault displacement, and it applies only to the first bounding case. Because it is a bounding case, the response exceeds the expected geologic response.

The first conservatism lies in the estimated fracture aperture for the bounding case. A maximum, ten-fold increase in fracture aperture is selected as a modeler's upper-bounding value and was justified in CRWMS M&O (2000e). The justification cites distance-strain relationships derived from models for a 1-m displacement along a strike-slip fault at Yucca Mountain (used as an analogue, though not directly representative of normal-fault response) and for a 1-m displacement on a theoretical normal fault. The changes in fracture apertures for the sensitivity analysis are derived by presuming a 10-m fault movement along the Solitario Canyon and multiplying the strains cited in the justification. The first conservatism results because the presumed 10-m displacement is conservative when compared to probabilistically determined and observed fault displacements.

Although the sensitivity study presumes a fault displacement bound of 10 m, the results of the PSHA (USGS 1998, Figures 8-2 and 8-3) indicate median and 85^{th} fractile fault displacements of the block-bounding faults of up to 3 m and approximately 5 m for the 10^{-8} annual-exceedance probability (see Assumptions 5.4 and 5.5 of this AMR (ANL-WIS-MD-000005)). Additionally, the maximum measured single-event Quaternary displacement (i.e., during the past 1.6 million years) on the Solitario Canyon fault is only 1.3 m (Ramelli et al. 1996, Table 4.7.3).

A second conservatism in the sensitivity analysis is in the conditions of the first bounding case: that a fault displacement could result in a "change in fracture properties occurring over the entire UZ domain." Field observations indicate the presence of gouge and brecciated zones only in limited proximity to fault planes, as described immediately below. This suggests that much of the strain will be mechanically dissipated within or near the fault plane itself. For instance, in the Solitario Canyon fault zone in the ECRB Cross Drift, the total displacement is approximately

260 m, but the gouge and brecciated zones are limited to less than 20 m from the fault (Mongano et al. 1999). Similarly, the Dune Wash fault as exposed in the ESF exhibits a cumulative offset of 65 m (Sweetkind et al. 1997, Table 21), but the zone of increased fracture frequency in the vicinity of the fault is only 6 to 7 m wide (Mongano et al. 1999). A third example is the Sundance fault in the ECRB Cross Drift. The Sundance fault has a presumed, though indeterminate, cumulative displacement of several meters. However, the footwall rock is intact at a distance of only 10 cm from the fault plane, and the hanging wall is slightly more fractured, with an intensely fractured zone about 1 m thick (Mongano et al. 1999). Distribution of the strain only in fault zones is used as the second, lower bounding case in the sensitivity analysis. Based on the ECRB Cross Drift observations, this second bounding case represents a lower, more realistic bound on the distribution of strain. Analysis of the second bounding case yields little effect on flow and transport.

Based on the results of the UZ sensitivity analyses (CRWMS M&O 2000e), changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration (CRWMS M&O 2000e, Section 7). Regardless of the fracture apertures used in the sensitivity study, the principle factor influencing flux through the UZ is infiltration at land surface, which is linked directly to climatic conditions. The TSPA-SR includes a range of climatic conditions ranging from present conditions to wetter conditions associated with glacial periods. Consequently, changes in fracture aperture will represent an insignificant effect compared to the influence of climate change.

The evaluation of changes to fracture systems presented in CRWMS M&O (2000e) relies upon conclusions that have been designated as TBV in that report. Therefore, the decision is *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose.

The SZ model uses the concept of flowing intervals, based on site data that indicates that only some of the fractures within the saturated zone contribute to the flow. Additionally, the SZ model implicitly includes fracture zones in the nominal case through consideration of horizontal anisotropy in permeability in the fractured volcanic units downgradient of the potential repository (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.7.1). Additionally, the SZ model also considers three cases of groundwater flow for both the horizontal isotropic and horizontal anisotropic conditions, resulting in six alternative groundwater flow fields (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.6.3.2)

Radionuclide transport is dependent on the flowing-interval porosity, the flowing-interval spacing, and the effective diffusion coefficient (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.5.2). The SZ flow model addresses the uncertainty for each of the three parameters (*Saturated Zone Flow and Transport Process Model Report* TDR-NBS-HS-000001, CRWMS M&O 2000o, Section 3.7.2).

The determination of flowing-interval spacing potentially affects matrix-diffusion processes in the SZ (*Probability Distribution for Flowing Interval Spacing* ANL-NBS-MD-000003 CRWMS M&O 2000p, Section 1.0). In particular, the SZ model likely underestimates the effect of matrix- diffusion processes in the SZ transport model because of the possible overestimation of the flowing-interval spacing (*Probability Distribution for Flowing Interval Spacing* ANL-NBS-

MD-000003 CRWMS M&O 2000p, Section 1.0). The overestimation occurs because the number of fractures that contribute to a flowing interval cannot be determined from the available data. Because each flowing interval probably has more than one fracture contributing to it, the true flowing-interval spacing could be less than the spacing determined from the probability distribution.

Future seismic activity could redistribute strain within the system. Redistribution of strain could open new fractures and close some existing fractures, as presumed by Gauthier et al. (1996, p. 163). The SZ model does not address these changes explicitly. However, because of the existing uncertainty considerations for the flow field, and because of the conservatism in the flowing-interval spacing used for the analysis, the effect of opening or closing of fractures and/or the creation of new fractures in the SZ, would be of no significance to flow-and-transport characteristics. Because flow characteristics are not significantly changed, dose is not significantly changed.

Changes in transport time are only significant if a release occurs during the period of regulatory concern (10,000 years). If there is no release, decreased travel times are not of significance. Changes in fracture properties have the potential to result in increased flux through the repository and, thereby, to affect the performance characteristics of the waste packages. However, the presence and durability of the drip shield will mitigate any increased flux during the repository performance period (10,000 years).

The effect of stress on emplacement drifts from dike propagation is examined in *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa, Section 6.3.2), which indicates that the effects are localized, perhaps up to three 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 2000s). The analysis indicates that stresses from fault displacements (which are also the focus for the analysis in CRWMS M&O 2000e, discussed above) are transmitted significant distances from the location of the fault. However, these induced stresses are of low consequence to dose, as discussed above.

In summary, based on the results of the UZ sensitivity analyses (CRWMS M&O 2000e), changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration (CRWMS M&O 2000e, Section 7). Furthermore, the presence and durability of the drip shield will mitigate any increased flux during the repository performance period (10,000 years). Because of the existing uncertainty considerations for the flow field and the conservatism in the flowing-interval spacing used for the SZ analysis, the effect of opening or closing of fractures and/or the creation of new fractures in the SZ would be of no significance to flow-and-transport characteristics. Because flow characteristics are not significantly changed, dose is not significantly changed. Consequently, this FEP is *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose.

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: See Attachment II

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

Features, Events, and Processes in SZ Flow and Transport ANL-NBS-MD-000002 (CRWMS M&O 2000r)*Treatment of*

Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: See the *YMP FEP Database* (CRWMS M&O, 2000c, Appendix D) and Attachment II for a list of related FEPs.

6.2.20 Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce 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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose.

Potential Consequence: Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS or waste packages, leading to a release of radionuclides.

Screening Argument: This FEP is fully discussed in *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000q, Section 6.7.8).

The effects of changes to fracture systems in the UZ fault zones have been investigated using a sensitivity approach (*Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020: CRWMS M&O 2000e). The sensitivity study is performed with the nominal UZ three-dimensional flow model and using several conservatisms that together provide bounding cases for determining whether changes in fractures will significantly impact repository performance. The analysis is performed using a dual-permeability, active-fracture flow model, and is based on the changing of fracture apertures that could be the result of strain conditions or other factors. Given a change in fracture aperture, other fracture hydrologic properties (permeability, capillary pressure, and porosity) are estimated through the use of theoretical models. CRWMS M&O (2000e) indicates that transport times are not sensitive to changes in the fracture aperture if limited to fault zones only.

The sensitivity study (CRWMS M&O 2000e) includes two bounding cases: (1) that changes in fracture properties occur over the entire UZ domain (fault zones and fractured rock), or (2) that the effects of fault displacement are limited to fracture-property changes in fault zones. These are modeling cases chosen to bound a presumed range of fracture-aperture changes resulting from fault movement. There are no direct observations for Yucca Mountain that relate stress caused by fault displacement to strain and resultant changes in fracture aperture. The bounding cases are used to simulate a response beyond that of the expected geologic response. The second bounding case (effects of fault displacement limited to fault zones) is applicable to this discussion and is justified based on conclusions by Sweetkind et al. (1997, pp. 68, 71) and field observations by Mongano et al. (1999), described below.

Two conclusions from Sweetkind et al. (1997, pp. 68, 71) suggest that faulting and fracturing are spatially related. The first is that the width of the zone of influence on fracture frequency in the immediate vicinity of a fault is, in general, quite narrow, ranging from less than 1 m to about 7 m from the fault. The second conclusion is that the width of the zone of influence in the immediate vicinity of a fault correlates, in a general way, with the amount of cumulative fault offset. Therefore, faults with the largest potential future displacement are the most likely to influence the potential repository block. Faults with tens of meters of cumulative offset (e.g., faults at ESF Stations 11+20 and 70+58) have zones of influence that range up to 6 to 7 m wide. Intrablock faults with very small amounts of cumulative offset (1 to 5 m) have zones of influence that are 1 to 2 m in width.

The presence of gouge and brecciated zones only in limited proximity to the fault planes, as described immediately below, suggests that much of the strain will be mechanically dissipated within or near the fault plane itself. For instance, in the Solitario Canyon fault zone in the ECRB Cross Drift, the total displacement is approximately 260 m, but the gouge and brecciated zones are limited to less than 20 m (Mongano et al. 1999). Similarly, the Dune Wash fault, as exposed in the ESF, exhibits a cumulative offset of 65 m (Sweetkind et al. 1997, Table 21), but the zone of increased fracture frequency in the vicinity of the fault is only 6 to 7 m wide (Mongano et al. 1999). A third example is the Sundance fault in the ECRB Cross Drift. The Sundance fault has a presumed, though indeterminate, displacement of several meters. However, the footwall rock is intact at a distance of only 10 cm from the fault plane. The hanging wall of the Sundance fault is slightly more fractured, with an intensely fractured zone about 1 m thick (Mongano et al. 1999).

A conservatism for the sensitivity analysis lies in the estimated fracture aperture for the bounding case. A maximum, ten-fold increase in fracture aperture is selected as a modeler's upper-bounding value and was justified in CRWMS M&O (2000e). The justification cites distance-strain relationships derived from models for a 1-m displacement along a strike-slip fault (used as an analogue, though not directly representative of normal-fault response) at Yucca Mountain and for a 1-m displacement on a theoretical normal fault. The changes in fracture apertures for the sensitivity analysis are derived by presuming a 10-m fault movement along the Solitario Canyon and multiplying the strains cited in the justification. The first conservatism results because the presumed 10-m displacement is conservative when compared to probabilistically determined and observed fault displacements.

Although the sensitivity presumes a fault-displacement bound of 10 m, the results of the PSHA (USGS 1998, Figures 8-2 and 8-3) indicate median and 85^{th} fractile fault displacements of the block-bounding faults of up to 3 m and approximately 5 m for the 10^{-8} annual-exceedance probability (see Assumptions 5.4 and 5.5 of this AMR (ANL-WIS-MD-000005)). Additionally, the maximum measured single-event Quaternary displacement (i.e., during the past 1.6 million years) on the Solitario Canyon fault is only 1.3 m (Ramelli et al. 1996, Table 4.7.3).

The results of the sensitivity study (CRWMS M&O 2000e) show that changes in fracture aperture confined to fault zones result in virtually no effect on transport behavior in the UZ (CRWMS M&O 2000e, Section 7). Because neither the flow nor transport are significantly affected by changes in fracture aperture in fault zones, changes in the stress state of fractures in faults do not provide a mechanism to significantly affect dose. Because dose is not significantly affected, the effects of faults and changes on the flow-properties of faults are *Excluded* based on low consequence to dose. However, the evaluation of changes to fracture systems relies upon conclusions that have been designated as TBV in CRWMS M&O (2000e); therefore, the FEP is *Excluded* from the TSPA-SR *(Preliminary)* based on low consequence to dose.

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 m within an hour of a simulated event. The simulated system returns to steady-state conditions within six 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).

In summary, effects in the UZ would either be transient in nature or would result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The effects of changes to fracture systems 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 2000e) and indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ, and increased fracture aperture applied over the entire UZ domain results in effects that are no more significant than other uncertainties related to infiltration (CRWMS M&O 2000e, Section 7). Therefore, the hydrologic response to seismic activity is of low consequence to dose and is *Excluded* from the TSPA-SR.

TSPA Disposition: "Changes in stress produce change in permeability of faults" and the associated Secondary FEPs are *Excluded* from the TSPA-SR *(Preliminary)*, as described under the TSPA Disposition.

IRSR-Issues: See Attachment II

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

Features, Events, and Processes in SZ Flow and Transport ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Treatment of Secondary FEPs: See Table 4 and Attachment II

Supplemental Discussion: See Screening Argument

6.2.21 Changes in Stress (due to Seismic or Tectonic Effects) Alter Perched Water Zones (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 and Regulatory Basis: *Excluded* from the TSPA-SR—Low consequence to dose.

Potential Consequence: Changes in stress due to all causes have the potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS or waste packages, leading to a release of radionuclides.

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

It seems problematic that a change in stress could, in itself, adequately seal a zone such that perched water develops. However, the generation of perched water above the repository as a result of seismic activity could potentially affect the flow of water to waste emplacement drifts. This potential effect is indirectly addressed by using focused flow in the seepage model abstraction.

Below the repository, the potential to release perched water as a result of stress changes and fracture openings due to seismic activity is considered. Hypothetically, such changes have the potential to result in a relatively sharp "pulse" of radionuclides, if the perched water contains radionuclides, and if the perched water is 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, are not expected to cause a significant "pulse" in radionuclide mass flux at the water table. Consequently, dose is not significantly changed and this FEP is *Excluded* from the TSPA-SR on the basis of low consequence to dose. See *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000q, Section 6.7.9) for a more detailed explanation).

TSPA Disposition: "Changes in stress alter perched water zones" and the associated Secondary FEPs are *Excluded* from the TSPA-SR, 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 2000q).

IRSR-Issues: See Attachment II

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

Treatment of Secondary FEPs: See Table 4 and Attachment II

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

7. CONCLUSIONS

Table 4 provides a summary of the Disruptive Events FEP-screening decisions and the basis for the decisions. Shaded FEPs are Primary, others are Secondary. All Secondary FEPs are shown in Table 4. Secondary FEP relationships to the Primary FEP are provided in Attachment II along with Secondary FEP Descriptions and the basis for the screening decision.

This document 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 confirmation activities will be reflected in subsequent revisions. The status of the technical product input information quality may be confirmed by review of the DIRS database.

Table 4. Summary of Disruptive Events FEPs Screening Decisions

YMP FEP Database Number	FEP Name	Screening Decision	Screening Decision Basis
1.2.01.01.00	Tectonic activity—large scale	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.01	Folding, uplift, or subsidence lowers facility with regard to current water table	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.02	Tectonic change to local geothermal flux causes convective flow in SZ and elevates water table	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.03	Tectonic folding alters dip of tuff beds, changing percolation flux	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.04	Uplift or subsidence changes drainage at the site, increasing infiltration	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.05	Uplift and subsidence	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.06	Effect of plate movements	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.07	Plate movement/tectonic change	*Excluded* from the TSPA-SR	Low consequence to dose

Table 4. Summary of Disruptive Events FEPs Screening Decisions (continued)

YMP FEP Database Number	FEP Name	Screening Decision	Screening Decision Basis
1.2.01.01.08	Uplift and subsidence	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.09	Regional vertical movements	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.10	Regional tectonic activity	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.11	Regional tectonics	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.12	Regional horizontal movements	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.13	Regional uplift and subsidence	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.01.01.14	Geological (events)	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.01.00*	Fractures	*Included* in the TSPA-SR for existing characteristics / *Excluded* from the TSPA-SR *(Preliminary)* for changes to characteristics	Does not satisfy a screening criterion / Low consequence to dose
1.2.02.01.01	Change in fracture properties	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.01.02	Fracturing	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.00*	Faulting	*Included* in the TSPA-SR for existing characteristics / *Excluded* from the TSPA-SR *(Preliminary)* for changes in fault properties and new faults	Does not satisfy a screening criterion/ Low consequence to dose for changes to existing characteristics and low probability for new faults
1.2.02.02.01	Faulting	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.02	Fault generation	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.03	Fault activation	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.04	Movements along small-scale faults	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.05	Faulting/Fracturing	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.06	Formation of new faults	*Excluded* from the TSPA-SR	Low Probability
1.2.02.02.07	Fault movement	*Excluded* from the TSPA-SR	Low consequence to dose

Table 4. Summary of Disruptive Events FEPs Screening Decisions (continued)

YMP FEP Database Number	FEP Name	Screening Decision	Screening Decision Basis
1.2.02.02.08	Normal faulting occurs or exists at Yucca Mountain	*Included* in the TSPA-SR for existing characteristics / *Excluded* from the TSPA-SR for changes in fault properties	Does not satisfy a screening criterion / Low consequence to dose for changes to existing characteristics
1.2.02.02.09	Strike-slip faulting occurs or exists at Yucca Mountain	*Included* in the TSPA-SR for existing characteristics / *Excluded* from the TSPA-SR for changes in fault properties and new faults	Does not satisfy a screening criterion / Low consequence to dose for changes to existing characteristics, and low probability for new faults
1.2.02.02.10	Detachment faulting occurs or exists at Yucca Mountain	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.11	Dip-slip faulting occurs at Yucca Mountain	*Included* in the TSPA-SR for existing characteristics / *Excluded* from the TSPA-SR for changes in fault properties and new faults	Does not satisfy a screening criterion / Low consequence to dose for changes to existing characteristics, and low probability for new faults
1.2.02.02.12	New fault occurs at Yucca Mountain	*Excluded* from the TSPA-SR	Low Probability
1.2.02.02.13	Old fault strand is reactivated at Yucca Mountain	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.14	New fault strand is activated at Yucca Mountain	*Excluded* from the TSPA-SR	Low Probability
1.2.02.02.15	Movements along major faults	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.16	Faulting (large scale, in geosphere)	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.02.02.17	Faulting exhumes waste container	*Excluded* from the TSPA-SR	Low Probability
1.2.02.03.00	Fault movement shears waste container	*Excluded* from the TSPA-SR	Low Probability
1.2.03.01.00	Seismic activity (Note: Includes faulting, and possible effects on hydraulic heads, recharge and discharge zones, rock stresses, drift integrity)	*Excluded* from the TSPA-SR *(Preliminary) for* indirect effects / *Excluded from the TSPA-SR (Preliminary)* for breaching of drip shield, and of the emplacement pallet and waste package / *Included* in the TSPA-SR for fuel-rod-cladding damage	Low consequence to dose / Low consequence to dose / Does not satisfy a screening criterion
1.2.03.01.01	Earthquakes	*Excluded* from the TSPA-SR	Low consequence to dose

Table 4. Summary of Disruptive Events FEPs Screening Decisions (continued)

YMP FEP Database Number	FEP Name	Screening Decision	Screening Decision Basis
1.2.03.01.02	Earthquakes	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.03.01.03	Earthquakes	*Excluded* from the TSPA-SR for indirect effects / *Excluded* from the TSPA-SR for breaching of drip shield, and of the emplacement pallet and waste package / *Included* in the TSPA-SR for fuel-rod-cladding damage	Low consequence to dose / Low consequent to dose / Does not satisfy a screening criterion
1.2.03.01.04	Seismicity	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.03.01.05	Seismicity	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.03.01.06	Seismicity	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.03.01.07	Seismic activity	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.03.02.00	Seismic vibration causes container failure	*Excluded from the TSPA-SR (Preliminary)* for breaching of drip shield, and of the emplacement pallet and waste package / *Included* in the TSPA-SR for fuel-rod cladding damage	Low consequence to dose / Does not satisfy a screening criterion
1.2.03.02.01	Container failure induced by microseisms associated with dike emplacement	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.03.03.00	Seismicity associated with igneous activity	*Excluded* from the TSPA-SR for indirect effects / *Included* in the TSPA-SR for fuel-rod cladding damage	Low consequence to dose / Does not satisfy a screening criterion
1.2.04.01.00	Igneous activity (Note: Also effects on faults, topography, rock stresses, groundwater temperatures, and drift integrity)	*Included* in the TSPA-SR for direct effects / *Excluded* from the TSPA-SR for indirect effects	Does not satisfy a screening criterion / Low consequence to dose
1.2.04.01.01	Volcanism	*Included* in the TSPA-SR for direct effects / *Excluded* from the TSPA-SR for indirect effects	Does not satisfy a screening criterion / Low consequence to dose
1.2.04.01.02	Magmatic activity	*Included* in the TSPA-SR for direct effects / *Excluded* from the TSPA-SR for indirect effects	Does not satisfy a screening criterion / Low consequence to dose
1.2.04.01.03	Magmatic activity	*Included* in the TSPA-SR	Does not satisfy a screening criterion

Table 4. Summary of Disruptive Events FEPs Screening Decisions (continued)

YMP FEP Database Number	FEP Name	Screening Decision	Screening Decision Basis
1.2.04.01.04	Magmatic activity	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.01.05	Volcanic activity	*Included* in the TSPA-SR for direct effects / *Excluded* from the TSPA-SR for indirect effects	Does not satisfy a screening criterion / Low consequence to dose
1.2.04.02.00 *	Igneous activity causes changes to rock properties	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.02.01	Dike provides a permeable flow path	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.02.02	Dike provides a barrier to flow	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.02.03	Volcanic activity in the vicinity produces an impoundment	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.02.04	Igneous activity causes extreme changes to rock geochemical properties	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.02.05	Intrusion (magmatic)	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.02.06	Dike-related fractures alter flow	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.02.07	Magmatic activity	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.03.00	**Igneous intrusion into repository**	***Included* in the TSPA-SR**	**Does not satisfy a screening criterion**
1.2.04.03.01	Sill provides a permeable flow path	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.03.02	Sill provides a flow barrier	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.03.03	Sill intrudes repository openings	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.03.04	Volcanism	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.03.05	Intruding dikes	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.04.00	**Magma interacts with waste**	***Included* in the TSPA-SR**	**Does not satisfy a screening criterion**
1.2.04.04.01	Magmatic volatiles attack waste	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.04.02	Dissolution of spent fuel in magma	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.04.03	Dissolution of other waste in magma	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.04.04	Heating of waste container by magma (without contact)	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.04.05	Failure of waste container by direct contact with magma	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.04.06	Fragmentation (Note: with subsequent damage to waste package)	*Included* in the TSPA-SR	Does not satisfy a screening criterion

Table 4. Summary of Disruptive Events FEPs Screening Decisions (continued)

YMP FEP Database Number	FEP Name	Screening Decision	Screening Decision Basis
1.2.04.05.00	Magmatic transport of waste	*Excluded* from the TSPA-SR for transport in liquid magma and other types of transport / *Included* in the TSPA-SR for transport through eruptive events	Low consequence to dose/ Does not satisfy a screening criterion
1.2.04.05.01	Direct exposure of waste in dike apron	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.05.02	Volatile radionuclides plate out in the surrounding rock	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.05.03	Entrainment of SNF in a flowing dike	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.04.06.00	Basaltic cinder cone erupts through the repository (Note: Also entraining waste)	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.06.01	Vent jump (formerly called "wander")	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.06.02	Vent erosion	*Included* in the TSPA-SR	Does not satisfy a screening criterion
1.2.04.07.00	Ashfall	*Included* in the TSPA-SR / *Excluded* from the TSPA-SR for *pyroclastic flow*	Does not satisfy a screening criterion / Low consequence to dose
1.2.10.01.00*	Hydrologic response to seismic activity	*Excluded* from the TSPA-SR *(Preliminary)*	Low consequence to dose
1.2.10.01.01	Fault movement pumps fluid from SZ to UZ (seismic pumping)	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.02	Fault creep causes short term fluctuation of the water table	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.03	New faulting breaches flow barrier controlling large hydraulic gradient to the north	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.04	Normal faulting produces a trap for laterally moving moisture in the Tiva Canyon unit	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.05	Head driven flow up from carbonates	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.06	Seismically-induced water table changes	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.07	Fault pathway through the altered Topopah Springs basal vitrophyre	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.08	Fault movement connects tuff and carbonate aquifers	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.09	Faults establishes pathway through UZ	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.10	Fault establishes pathway through the SZ	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.11	Fluid supplied by a fault migrates down the drift	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.01.12	Fault intersects and drains condensate zone	*Excluded* from the TSPA-SR	Low consequence to dose

Table 4. Summary of Disruptive Events FEPs Screening Decisions (continued)

YMP FEP Database Number	FEP Name	Screening Decision	Screening Decision Basis
1.2.10.01.13	Flow barrier south of the site blocks flow, causing water table to rise.	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.02.00*	**Hydrologic response to igneous activity (Note: Includes groundwater flow directions; water level, groundwater chemistry, temperature; changes in rock properties)**	***Excluded* from the TSPA-SR**	**Low consequence to dose**
1.2.10.02.01	Interaction of water table with magma	*Excluded* from the TSPA-SR	Low consequence to dose
1.2.10.02.02	Interaction of unsaturated zone pore water with magma	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.01.00	**Rockfall (large block)**	***Excluded* from the TSPA-SR *(Preliminary)***	**Low consequence to dose**
2.1.07.01.01	Rockbursts in container holes	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.01.02	Cave ins	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.01.03	Cave in (in waste and EBS)	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.01.04	Roof falls	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.02.00	**Mechanical degradation or collapse of drift**	***Excluded* from the TSPA-SR *(Preliminary)***	**Low consequence to dose**
2.1.07.02.01	Stability (in the waste and EBS)	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.02.02	Mechanical (events and process in the waste and EBS)	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.02.03	Rockfall stopes up fault	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.02.04	Rockfall (rubble) (in waste and EBS)	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.02.05	Mechanical failure of repository	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.02.06	Subsidence/collapse	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.02.07	Vault collapse	*Excluded* from the TSPA-SR	Low consequence to dose
2.1.07.02.08	Creeping rock mass	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.01.00* *	**Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock**	***Excluded* from the TSPA-SR *(Preliminary)***	**Low consequence to dose**
2.2.06.01.01	Stress-produced porosity changes	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.01.02	Stress-produced permeability changes	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.01.03	Stress-produced permeability changes	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.01.04	Regional stress regime	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.01.05	Regional stress regime	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.01.06	Regional stress regime	*Excluded* from the TSPA-SR	Low consequence to dose

Table 4. Summary of Disruptive Events FEPs Screening Decisions (continued)

YMP FEP Database Number	FEP Name	Screening Decision	Screening Decision Basis
2.2.06.01.07	Stress field (in geosphere)	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.01.08	Changes in stress field	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.01.09	Changes in regional stress	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.01.10	Stress changes - hydrogeological effects	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.02.00* *	Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults	*Excluded* from the TSPA-SR *(Preliminary)*	Low consequence to dose
2.2.06.02.01	Aseismic alteration of permeability along and across faults	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.02.02	Fracture dilation along faults creates zones of enhanced permeability	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.02.03	Relaxation of thermal stresses by fault movement	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.02.04	Seismically-stimulated release of thermo-mechanical stress on bounding faults	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.02.05	Relaxation of thermal stresses by fault movement	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.03.00 *	Changes in stress (due to seismic or tectonic effects) alter perched water zones	*Excluded* from the TSPA-SR	Low consequence to dose
2.2.06.03.01	Perched zones develop as a result of stress changes	*Excluded* from the TSPA-SR	Low consequence to dose

Notes: Shaded Items are Primary FEPs; others are Secondary FEPs.
* These FEPs are addressed in detail by other FEP AMRs; see the *YMP FEP Database* (CRWMS M&O 2000c, Appendix D) and Attachment II. Secondary FEPs are addressed in the related FEP AMRs.

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8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

64 FR 46976. Environmental Radiation Protection Standards for Yucca Mountain, Nevada. Readily Available

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

AP-2.21Q. REV 0, ICN 0 *Quality Determinations And Planning for Scientific, Engineering, And Regulatory Compliance Activities.* Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL. 20000802.0003.

AP-3.10Q, REV 2, ICN 3 *Analyses and Models.* Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL. 20000918.0282.

AP-3.15Q, REV 1, ICN 2. *Managing Technical Product Inputs.* Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL. 20000713.0363.

AP-SI.1Q, REV 2, ICN4, ECN 1. *Software Management.* Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20001019.0023

AP-SV.1Q, REV 0, ICN 2. *Control of the Electronic Management of Information.* Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000831.0065.

NLP-2-0 REV 5, ICN 1. *Determination of Importance Evaluations.* Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000713.0360

QAP-2-0, REV 5, ICN 1. *Conduct of Activities* Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19991109.0221.

QAP-2-3, REV 10, ICN 0. *Classification of Permanent Items.* Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19990316.0006

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ATTACHMENT I
GLOSSARY

aperture – The gap between two walls or faces of a fracture.

asperity – A measure of the roughness of the area of contact between two surfaces of a fracture.

background earthquake – An earthquake that does not produce ground breakage, hence is 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 of less the 6.0.

basalt – A dark-colored, fine-grained volcanic or intrusive rock (dike or sill intrusion) consisting 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 friable to hard, off-white, crudely layered to finely laminated intervals near the surface of stony desert soils; several cm or more thick. Old, thick caliche intervals (calcretes) have the texture and hardness of concrete aggregate.

colluvial slope – A hill slope mantled with loose, heterogeneous soil and rock fragments that 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 land 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 the Crater Flat basin which lies immediately to the west of Yucca Mountain.

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

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

detachment faulting – A style of normal faulting wherein large, extensional 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 *Included* in the TSPA-SR FEP, and 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 the potential to affect disposal-system performance and that occurs during an interval that is short compared to the period of performance.

excluded FEP – A FEP that is identified by the FEP screening process as not requiring modeling in the quantitative TSPA.

expected FEP – An included FEP that, for the purposes of the TSPA, is presumed 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 a 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. 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.

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

flowing interval – A fracture or fractured zone that transmits flow in the SZ.

folding – Bending in strata. 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 termed 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 an intrusive or extrusive 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.

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

geothermal gradient – The rate of increase of temperature with depth in the earth

heat flow – The amount of heat energy leaving the earth's crust, measured in Heat Flow Units (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 on 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 structure (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 rock mass surrounding an excavation (by the intersection of three or more planes of structural discontinuity). These blocks are capable of displacement so that they are likely to move into the drift 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, which can occur due to 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 the process of convection and buoyancy. Mantle plumes are typically hundreds 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. Playas have, 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 at which such water stands in a well. The water table is a particular type of potentiometric surface pertaining to an unconfined aquifer in which the surface is in equilibrium with atmospheric pressure.

Primary FEP – A description of a single feature, event, or process, or a few closely related or coupled processes or events that can be addressed by a specific screening discussion. A Primary FEP may also include one or more related Secondary FEPs that are covered by the same screening discussion.

process – A natural or anthropogenic phenomenon that has the 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 1.6 Ma to present; includes the Pleistocene and Holocene Epochs.

reference biosphere – The description of the environment inhabited by the critical group. The reference biosphere comprises the set of specific biotic and abiotic characteristics of the environment, including but not necessarily limited to, climate, topography, soils, flora, fauna, and human activities.

regional slope – The surface defined by 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 – A sudden and often violent failure of masses of rocks in quarries, tunnels, or mines. It is an uncontrolled disruption of rock associated with a violent release of energy additional to that derived from falling rock fragments.

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

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.

Secondary FEP – A FEP that is (1) redundant to another FEP (e.g., several contributors identified the same FEP), (2) specific to a non-YMP program and captured in a more general sense by a different YMP-specific FEP, or (3) better captured or subsumed in another similar but more broadly defined YMP-specific FEP. Each Secondary FEP is mapped to a Primary FEP and is completely addressed by the screening discussion of the Primary FEP.

seismic activity – 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, vault, or drift begins to curve; for circular cross-sections, this corresponds to the vertical 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 – See fault strand.

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 tectonic forces as crustal plates interact.

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 produced by tectonic processes, including mountain building (orogeny), regional uplift and subsidence; the general expression of tectonic process through time and space.

terrain relief – For some defined area of the earth's surface , it is 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 that they may affect repository design or performance.

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

vertical axis rotation – Folding referenced to a vertical axis. Hence, folded 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, or cone formation comprising 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 feeds 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 were partially melted together (welded) during compaction of the ash bed while the ash was still hot.

ATTACHMENT II
PRIMARY FEPs RELATIONSHIP TO SECONDARY FEPs, KEY TECHNICAL ISSUES, AND INTEGRATED SUBISSUES

Primary FEP: Tectonic Activity—Large Scale

FEP Number: **1.2.01.01.00**	**Primary 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.

Primary Assigned to: Disruptive Events FEPs AMR

Screening Decision: *Excluded* from the TSPA-SR | **Screening Decision Basis:** Low consequence to dose

Number of Secondaries: *14* **Screening Decisions:** *All Excluded* from the TSPA-SR

Geologic Process: Tectonism

Potential Consequences: Alteration of physical and thermo-hydrologic properties of the geosphere could impact UZ and SZ flow-and-transport properties, thereby affecting dose. These changes could also alter the groundwater flux through the repository and the amount of water contacting elements of the EBS and the waste packages and, thereby, alter the waste form and/or performance characteristics of these elements.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains. Yucca Mountain is in an overall subsiding structural basin with a waning rate of subsidence (Fridrich 1999).

Discussion: The geologic processes mentioned in this Primary FEP occur on a geologic time scale. Consequently, the physical and thermo-hydrologic properties will not experience significant alterations within the period of regulatory concern (10,000 years). Because only insignificant changes will occur, there is negligible potential for dose to be affected, and tectonic activity is, therefore, of low consequence to dose.

Relation of Elements of the Primary FEP Description to Secondary FEPs	
Regional uplift, subsidence or folding, mountain building	Lower facility with regard to current water table (1.2.01.01.01) Change local geothermal flux, change convective flow in SZ, elevate water Table (1.2.01.01.02) Dip of beds altered by folding changing percolation (1.2.01.01.03) Drainage (surface) at site changes and increases infiltration (1.2.01.01.04) Uplift and subsidence (1.2.01.01.05) Uplift and subsidence (1.2.01.01.08) Regional vertical movements (1.2.01.01.09) Regional tectonic activity (1.2.01.01.10) Regional tectonics (1.2.01.01.11) Regional horizontal movements (1.2.01.01.12) Regional uplift and subsidence (1.2.01.01.13)
Other processes from plate movement	Effect of plate movements (FEP 1.2.01.01.06) Plate movement/tectonic change (FEP 1.2.01.01.07) Geological (events) (FEP 1.2.01.01.14)

Reference(s): Supporting documentation for the process of Tectonic activity—large scale is found in the PSHA expert elicitation (USGS 1998 and CRWMS M&O 2000k).

Primary FEP: Tectonic Activity—Large Scale (continued)

Links to FEPs that examine related but distinct effects and consequences

Faulting and seismicity are associated with tectonism. Effects on the EBS, waste package, and waste form elements from faulting or seismicity events or processes not described under this Primary FEP are examined under the following Primary FEPs:

Fractures (1.2.02.01.00)
Faulting (1.2.02.02.00)
Fault movement shears waste container (1.2.02.03.00)
Seismic activity (1.2.03.01.00)
Seismic vibration causes container failure (1.2.03.02.00)
Rockfall (large block) (2.1.07.01.00)
Mechanical degradation or collapse of drift (2.1.07.02.00)
Movement of containers (2.1.07.03.00)

Tectonism models supporting the preceding Primary FEPs are consistent with those applied to volcanic activity and are linked to the Primary FEPs "Seismicity associated with igneous activity" (1.2.03.03.00) and "Igneous activity" (1.2.04.01.00) .

Links to FEPs that examine similar effects and consequences

Metamorphism (1.2.05.00.00)
Hydrothermal activity (1.2.06.00.00)
Hydrologic response to seismic activity (1.2.10.01.00)
Water-table rise (1.3.07.02.00)
Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock (2.2.06.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults (2.2.06.02.00)
Changes in stress (due to seismic or tectonic effects) alter perched water zones (2.2.06.03.00)

Links to IRSRs

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS4: Tectonic Framework of the Geologic Setting

Integrated Subissues / Related KTI Subissues:

ENG2: Mechanical Disruption of Barriers / IA1, IA2, SDS1, SDS2, SDS3, RDTME2, RDTME3
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC4, USFIC5, SDS3, SDS4
Direct 1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, IA1, IA2, SDS1, SDS4

Primary FEP: Tectonic Activity—Large Scale (continued)

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Folding, uplift or subsidence lowers facility with regard to current water table

FEP Number: 1.2.01.01.01	**Originator FEP Description**: Folding, uplift or subsidence lowers the facility with respect to the current water table. This shortens the distance between the repository and the water table or puts the repository below the water table. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequence: This FEP is concerned with the change in relative position of water table and the repository. This could affect transport times or result in flooding of the repository.

Discussion: Folding, uplift, and subsidence occur on a geologic time scale (2 mm/yr) and would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). At present, the water table is 200-400m below the repository. Within the regulatory period, the imperceptibly small geologic changes that would occur as a result of these processes are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Tectonic change to local geothermal flux causes convective flow in SZ and elevates water table

FEP Number: 1.2.01.01.02	**FEP Description**: The in situ heat flow at the site changes because of tectonic change. Changes in the temperature gradients at the site lead to convective flow in the saturated-zone and elevate the water table. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is concerned with the change in relative position of repository and water table.

Discussion: Tectonically induced changes in geothermal gradients leading to convective flow changes in the saturated zone resulting in subsequent change in water-table elevation would occur on a geologic time scale and would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). Therefore, within the period of regulatory concern (10,000 years), the imperceptibly small geologic changes that would occur as a result of these processes are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale (continued)

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Tectonic folding alters dip of tuff beds, changing percolation flux

FEP Number: 1.2.01.01.03	**Originator FEP Description**: Tectonic folding changes the dip of the tuff beds, thereby changing the local percolation flux to values not currently observed. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: The change in dip could be an increase, a decrease, or a change of dip direction. Consequence of the preceding could be an increase or decrease of flux in a given area of the repository. The originator's description presumes that dip constrains percolation. This may not be the case in a fracture-flow dominated system.

Discussion: Folding occurs on a geologic time scale and would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). Regional compressive stresses that could produce uplift or depression related to subhorizontal (compressive) fold axes have not operated in the Yucca Mountain region within the past 50 M.y. (Keefer and Fridrich 1996). Folding is more likely to be expressed as rollover associated with normal faulting (Fridrich et al. 1996, p. 2-29). Any further rollover is expected to result in a steepening of about 2 degrees in a million years. Such a minor change in dip will not significantly affect the flow system. Consequently tectonic-folding does not represent a mechanism to significantly affect dose. Accordingly, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Uplift or subsidence changes drainage at the site, increasing infiltration

FEP Number: 1.2.01.01.04	**Originator FEP Description**: Uplift or subsidence changes the drainage at the site, thereby changing the local percolation flux to values not currently observed. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Uplift or subsidence potentially causes a change in surface topography by changing elevations, dips of the strata that outcrop, etc., resulting in changes in surface drainage that could affect infiltration and the strata exposed as routes for infiltration and, therefore, local percolation flux.

Discussion: Uplift and subsidence and the subsequent consequences described above occur on a geologic time scale and would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). Therefore, within the period of regulatory concern (10,000 years), the imperceptibly small geologic changes that would occur as a result of these processes do not significantly alter the flow system and are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale (continued)

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Uplift and subsidence

FEP Number: 1.2.01.01.05	**Originator FEP Description**: There is continuous ongoing land uplift in Sweden. The maximum rate of uplift in northern Sweden is 9mm per year, in Stockholm 5 mm and in Scania about 0 mm. Etc. (Joint SKI/SKB)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* This FEP description is particular to uplift in Sweden that is due to glacial rebound. It is inferred that the intention of this FEP is to analyze the effects of uplift and subsidence at potential repository sites including Yucca Mountain. The specific consequences of concern are those that would affect the properties of the UZ and SZ.

Discussion: Uplift, subsidence, and folding occur on a geologic time scale that would require much longer periods to produce a significant effect than the period of regulatory concern (10,000 years). Therefore, the imperceptibly small geologic changes that would occur as a result of these processes do not significantly alter the flow system and are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Effect of plate movements

FEP Number: 1.2.01.01.06	**Originator FEP Description**: Movements of tectonic plates could affect disposal system performance. (Joint SKI/SKB)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Consequences are those in the Primary FEP description and include regional uplift, subsidence, folding, and mountain building as events that could affect the thermo-hydrologic properties of the geosphere. Plate movements may also be a factor in the occurrence of seismic and igneous event.

Discussion: Plate movements occur on a geologic time scale and would require much longer periods to produce a significant effect than the period of regulatory concern (10,000 years). Therefore, the imperceptibly small geologic changes that would occur as a result of these processes do not significantly alter the flow system and are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale (continued)

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Plate movements/tectonic change

FEP Number: 1.2.01.01.07	**Originator FEP Description**: none (NEA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: It is conjectured that the intention of this FEP is to analyze the effects of overall tectonic change caused by crustal plate movements. Consequences are those in the Primary FEP description and include regional uplift, subsidence, folding, and mountain building that could affect the thermo-hydrologic properties of the geosphere.

Discussion: Plate movements occur on a geologic time scale and would require much longer periods to periods to produce a significant effect than the period of regulatory concern (10,000 years). Therefore, the imperceptibly small geologic changes that would occur as a result of these processes do not significantly alter the flow system and are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Uplift and subsidence

FEP Number: 1.2.01.01.08	**Originator FEP Description**: none (NEA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: It is conjectured that the intention of this FEP is to analyze the effects of uplift and subsidence at potential repository sites including Yucca Mountain. The specific consequences of concern are those that would affect the properties of the UZ and SZ.

Discussion: Uplift, subsidence, and folding occur on a geologic time scale that would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). Therefore, the imperceptibly small geologic changes that would occur as a result of these processes do not significantly alter the flow system and are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Regional vertical movements

FEP Number: 1.2.01.01.09	**Originator FEP Description**: The up-doming of the crystalline basement in the Southern Black Forest region (which has continued over the last several tens of million years) will lead to a maximum uplift of 200 to 400 m in the next one million years in Area West and Area East, respectively. The relative movement will be absorbed by movement on existing faults.(NAGRA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP description is specific to updoming of basement crystalline rocks for a repository site in Europe. It is conjectured that the intention of this FEP is to analyze the effects of uplift on a regional scale. The specific consequences of concern are those that would affect the properties of the UZ and SZ.

Discussion: Uplift occurs on a geologic time scale that would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). Therefore, the imperceptibly small geologic changes that would occur as a result of these processes do not significantly alter the flow system and are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale (continued)

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Regional tectonic activity

FEP Number: 1.2.01.01.10	Originator FEP Description: Natural tectonic movements in the form of uplift, subsidence and regional warping may induce faulting and changes to the hydrogeologic regime with consequent changes to the radionuclide transport pathways. (UK-HMIP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: The consequences of concern are as stated in the FEP, with the changes to hydrogeologic regime and consequent changes to radionuclide transport pathways interpreted as meaning changes in flow and transport in the UZ and/or SZ.

Discussion: Uplift, subsidence, and regional warping occur on a geologic time scale and would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). Therefore, the imperceptibly small geologic changes that would not significantly alter the flow system and are of low consequence to dose. The consequences of faulting as a FEP are examined under the Primary FEP "Faulting" (1.2.02.02.00), which is linked to the Primary FEP "Fractures" (1.2.02.01.00).

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Regional tectonics

FEP Number: 1.2.01.01.11	Originator FEP Description: The tectonic setting and structural features of the area around the WIPP have been characterized [. . .]. In summary, there is no geological evidence for Quaternary regional tectonics in the Delaware Basin. (WIPP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is specific to the Waste Isolation Pilot Project (Source identifier code W1.004). It is conjectured that the intention of this FEP is to analyze the effects of uplift and subsidence at potential repository sites including Yucca Mountain. Consequences of concern are as stated in the FEP with changes to hydrogeologic regime and consequent changes to radionuclide-transport pathways interpreted as meaning changes in flow and transport in the UZ and/or SZ.

Discussion: Uplift, subsidence, and folding occur on a geologic time scale that would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). Therefore, the imperceptibly small geologic changes that would occur as a result of these processes do not significantly alter the flow system and are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale (continued)

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Regional horizontal movements

FEP Number: **1.2.01.01.12**	**Originator FEP Description**: Based on the anticipated tectonic evolution in the Kaisten-Bottstein-Leuggern area it is expected that there will be horizontal movements along faults and that, within the zone of influence of the Jura over thrust, the sedimentary cover which has been sheared off from the basement will be transported further north. There have as yet been no measurements of horizontal movements and the assumed values are based on geological considerations. (NAGRA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: The presumption is that the intention of this FEP is to analyze the tectonic effect of overthrusting. The specific consequences of concern are those that would affect the properties of the UZ and SZ.

Discussion: This FEP was analyzed under the Tectonic Activity Primary FEP because the principal geologic process mentioned was overthrusting, which is a large-scale tectonic consequence of compression of the Earth's crust. Overthrusting occurs on a geologic time scale and would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). Additionally, there is no indication that overthrusting is a dominant process at Yucca Mountain, which is in an extensional basin. Therefore, the imperceptibly small geologic changes that would occur as a result of these processes do not significantly alter the flow system and are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Regional uplift and subsidence

FEP Number: **1.2.01.01.13**	**Originator FEP Description**: There are no reported stress measurements from the Delaware Basin but a low level of regional stress has been inferred from the geological setting of the area. etc. (WIPP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: The FEP as written is specific to the Waste Isolation Pilot Project (WIPP). It is inferred from the description that the intention of this FEP is to consider the effects of regional stress in light of the geological setting. This inference leads to consideration under Tectonic Activity. This FEP is considered similar to Secondary FEPs 1.2.01.01.09, 1.2.01.01.10, 1.2.01.01.11, and 1.2.01.01.12, which deals with uplift and subsidence. The specific consequences of concern are those that would affect the properties of the UZ and SZ.

Discussion: Uplift, subsidence, and folding occur on a geologic time scale that would require much longer periods to have a significant effect than the period of regulatory concern (10,000 years). Therefore, the imperceptibly small geologic changes that would occur as a result of these processes do not significantly alter the flow system and are of low consequence to dose.

Primary FEP: Tectonic Activity—Large Scale
Secondary FEP: Geological (events)

FEP Number: **1.2.01.01.14**	**Originator FEP Description**: none (NEA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: No description of the FEP was provided by the originator and the FEP name is too generalized to reasonably infer which geologic processes are of concern.

Discussion: FEP description from the source information is inadequate to allow analysis. However, multiple other FEPs address specific types of geologic events that could be of concern. Because other, more-specific geologic events are considered within the FEP process, any inferred events are presumably addressed by other FEPs. Therefore, this FEP would be of no further (i.e., low) consequence to dose.

Primary FEP: Fractures

FEP Number: 1.2.02.01.00	**Primary 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.
Primary Assigned to: Disruptive Events FEPs, Unsaturated Zone FEPs, Near Field Environment FEPs	
Screening Decision: *Included* in the TSPA-SR for existing features, *Excluded* from the TSPA-SR *(Preliminary)* for changes of fracture characteristics	**Screening Decision Basis:** Does not satisfy a screening criterion / Low consequence to dose
Number of Secondaries: *2* **Screening Decisions:** *Included* in the TSPA-SR / *Excluded* from the TSPA-SR	

Geologic Process: Fracturing, particularly stemming from thermal, seismic, or tectonic events, and as it pertains to the influence on flow and transport.

Potential Consequences: Groundwater flow in the Yucca Mountain region and transport of any released radionuclides may take place along fractures. The rate of flow and the extent of transport in fractures is influenced by characteristics such as orientation, aperture, asperity, fracture length, connectivity, and the nature of any linings or fracture fillings (i.e., infills). Generation of new fractures and reactivation of pre-existing fractures may significantly change the fracture characteristics and, thereby, alter the flow-and-transport paths, thereby affecting dose. These changes could also alter the groundwater flux through the repository and the amount of water contacting elements of the EBS and the waste packages and, thereby, alter the waste form and/or performance characteristics of these elements.

Geologic Setting: Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The peak phase of tectonism took place 12 to 11.6 Ma. The width of the zone of influence on fracture frequency in the immediate vicinity of a fault is, in general, quite narrow, ranging from less than 1 m to about 7 m from the fault and correlates, in a general way, with the amount of cumulative fault offset. The width of the zone of influence around a fault does not appear to be related to depth. The amount of deformation associated with faults appears, in part, to be dependent upon which lithologic unit is involved in the faulting. Lithostratigraphic controls affect fracture spacing, type, number of fracture sets, continuity of individual fractures within each lithostratigraphic zone, and they also affect the fracture connectivity of the network as a whole.

Discussion: Existing fracture characteristics are *Included* in the TSPA-SR for both the UZ and the SZ. Unless stress vectors acting on Yucca Mountain were to deviate markedly from those acting within the past few million years, the shear strength of intact rock will be exceeded in the presence of fracture sets favorably oriented to accommodate increased stress. This conclusion is supported qualitatively by the results of the PSHA (USGS, 1998), which concludes that minimal displacement in intact rock is of low probability. Additionally, site observations indicate reactivation features in existing fractures. Consequently, the formation of new fractures is of low probability.

The SZ flow model addresses existing fractures through the use of flowing intervals, which are a subset of water-conducting features within the fracture system. Both the UZ and SZ flow models include fractures and uncertainty in the hydrologic-and-transport properties of the fracture system.

The matrix- and fracture-parameter values for the hydrogeologic units and the faults are included in the analysis performed in the *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e). The analysis is based on the changing of fracture apertures. Given a change in fracture aperture, other hydrologic properties of fractures (permeability, capillary pressure, and porosity) were estimated through the use of theoretical models. Although the analysis particularly addressed the effects of fault displacement, the analysis is mechanistically based only on the change of fracture apertures, regardless of the proximal cause of the change. Therefore, the analysis is potentially applicable to fracturing stemming from thermal, seismic, or tectonic events, as long as the amount of induced changes in fracture apertures are within the range of apertures evaluated in the analysis. This analysis showed that changes in fracture aperture (0.2 times to 10 times the existing fracture aperture) had minimal impact on UZ flow characteristics.

Primary FEP: Fractures (continued)

The analysis (*Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 CRWMS M&O 2000e) includes two bounding assumptions: (1) the change in fracture properties occurs over the entire UZ domain (fault zones and fractured rock; or (2) that the effect of fault displacement is limited to fracture-property changes in fault zones. CRWMS M&O (2000e) indicated that transport times were not sensitive to changes in the fracture aperture. The results of the analysis are currently being reanalyzed using a dual-permeability, active-fracture flow model, to determine the effect of active fractures on transport time and flux.

Because of the existing consideration of uncertainty in fracture properties, the low probability of the formation of new fractures and the insensitivity of transport times in the UZ to changes in fracture aperture, changes in fracture properties are not likely to significantly alter the rate of flow, significantly alter the fracture characteristics, or otherwise alter the groundwater flux through the repository, and are, therefore, of low consequence to dose.

Relation of Elements of Primary FEP Description to Secondary FEPs	
Groundwater flow and transport of radionuclides occurs along fractures	Change in fracture properties (1.2.02.01.01)
Generation of new fractures and reactivation of pre-existing fractures may significantly change the fracture characteristics	Change in fracture properties (1.2.02.01.01)

References: Supporting documentation for the evaluation of the impact of changes of fracture apertures is provided in CRWMS M&O (2000e). Fracture flow characteristics in the UZ and SZ are described in CRWMS M&O (2000l), CRWMS M&O (2000o), CRWMS M&O (2000p). See also *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000q) and *Features, Events, and Processes in SZ Flow and Transport* ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Links to FEPs that examine related but distinct effects and consequences

Fracturing is a factor in multiple FEP considerations including flow and transport and is also closely related to faulting issues. It also provides a key parameter in analysis of rockfall and drift stability. Effects on the EBS, waste packages, and waste-form elements not described under this Primary are examined under the following Primary FEPs:

Tectonic activity—large scale (1.2.01.01.00)
Faulting (1.2.02.02.00)
Rockfall (large block) (2.1.07.01.00)
Mechanical degradation or collapse of drift (2.1.07.02.00)

Links to FEPs that examine similar effects and consequences

Hydrologic response to seismic activity (1.2.10.01.00)
Flow through invert (2.1.08.05.00)
Rock properties of host rock and other units (2.2.03.02.00)
Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock (2.2.06.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults (2.2.06.02.00)
Changes in stress (due to seismic or tectonic effects) alter perched water zones (2.2.06.03.00)
Focusing of unsaturated flow (fingers, weeps) (2.2.07.04.00)
Fracture flow in the unsaturated zone (2.2.07.08.00)
Water conducting features in the saturated zone (2.2.07.13.00)

Primary FEP: Fractures (continued)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS3: Fractures
USFIC3: Shallow Infiltration
USFIC4: Deep Percolation

Integrated Subissues / Related Subissues:

ENG2: Mechanical Disruption of Barriers / RDTME2, SDS1, SDS2, SDS4, RDTME3
ENG3: Quantity and Chemistry of Water Contacting the Waste Package and Waste Form / ENFE1, ENFE2, CLST1, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, USFIC 5, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, USFIC5, ENFE1, SDS3
UZ3 Geo: Radionuclide Transport in the UZ
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3
SZ2 Geo: Radionuclide Transport in the SZ

Primary FEP: Fractures
Secondary FEP: Change in fracture properties

FEP Number: **1.2.02.01.01**	**Originator FEP Description**: Groundwater flow in the region of the WIPP and transport of any released radionuclides may take place along fractures. The rate of flow and the extent of transport will be influenced by fracture characteristics such as orientation, aperture, asperity, fracture length and connectivity, and the nature of any linings or infills. etc. (WIPP)
Screening Decision: *Included* in the TSPA-SR existing characteristics / *Excluded* from the TSPA-SR changes in fracture properties	**Screening Decision Basis**: *Included* in the TSPA-SR Does not satisfy a screening criterion. *Excluded* from the TSPA-SR Low consequence to dose

Potential Consequences: This FEP is inferred to apply to the significance changes in fracture characteristics that could impact fracture flow at Yucca Mountain. Generation of new fractures and reactivation of pre-existing fractures may significantly change the fracture characteristics and, thereby, alter the flow-and-transport paths, thereby affecting dose. These changes could also alter the groundwater flux through the repository and the amount of water contacting elements of the EBS and the waste packages and, thereby, alter the waste form and/or performance characteristics of these elements.

Discussion: Because of the existing consideration of uncertainty in fracture properties and the low probability of the formation of new fractures, changes in fracture properties are not likely to significantly alter the rate of flow, the fracture characteristics, or otherwise alter the groundwater flux through the repository, and are, therefore, of low consequence to dose.

Primary FEP: Fractures (continued)

Primary FEP: Fractures
Secondary FEP: Fracturing

FEP Number: 1.2.02.01.02	**Originator FEP Description**: (none) (NEA)
Screening Decision: *Included* in the TSPA-SR existing characteristics / *Excluded* from the TSPA-SR changes in fracture properties	**Screening Decision Basis**: *Included* in the TSPA-SR Does not satisfy a screening criterion. *Excluded* from the TSPA-SR Low consequence to dose

Potential Consequences: It is conjectured that the intention of this FEP is to analyze the same effects and consequences as for the Primary FEP description

Discussion: Existing fracture properties are *Included* in the TSPA-SR. Because of the existing consideration of uncertainty in fracture properties and the low probability of the formation of new fractures (inferred from the results of the PSHA (USGS 1998)), changes in fracture properties are not likely to significantly alter the rate of flow, the fracture characteristics, or otherwise alter the groundwater flux through the repository, and are, therefore, of low consequence to dose.

Primary FEP: Faulting

FEP Number: **1.2.02.02.00**	**Primary 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.
Primary Assigned to: Disruptive Events FEPs, Unsaturated Zone FEPs, Saturated Zone FEPs	
Screening Decision: *Included* in the TSPA-SR for existing characteristics, *Excluded* from the TSPA-SR *(Preliminary)* for changes of fault characteristics and for new faults	**Screening Decision Basis**: *Included* in the TSPA-SR Does not satisfy a screening criterion / *Excluded* from the TSPA-SR *(Preliminary)* Low consequence to dose for changes of fault characteristics and Low Probability of new faulting.
Number of Secondaries: *16* **Screening Decisions**: *Included* in the TSPA-SR / *Excluded* from the TSPA-SR	

Geologic Process: Faulting

Potential Consequences: Faulting is a potentially disruptive process with effects that include earthquakes (i.e., vibratory ground motion), rock-strength failure, and sudden changes in geometry and physical properties of the rock adjacent to the fault that are potentially relevant to changes in hydrology and integrity of the potential repository. The effects of vibratory ground motion are addressed under other Primary FEPs, including Seismic activity (1.2.03.01.00); Seismic vibration causes container failure (1.2.03.02.00); Rockfall (large block) (2.1.07.01.00); Mechanical degradation or collapse of drift (2.1.07.02.00) and Movement of containers (2.1.07.03.00).

Faulting may alter the rock permeability in the rock mass or fractures 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 (e.g., extension or expansion) of existing faults may enhance the groundwater flow, thus decreasing the transport times for potentially released radionuclides. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and the waste packages, leading in turn to the potential for release of radionuclides.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Yucca Mountain is in an overall subsiding structural basin with a waning rate of subsidence (Fridrich 1999). The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The predominate forms of faulting in the Yucca Mountain region are dip-slip faulting (primarily as normal faults, but reverse faults are present) and strike-slip faulting. The peak phase of tectonism took place 12 to 11.6 Ma. The width of the zone of influence on fracture frequency in the immediate vicinity of a fault is, in general, quite narrow, ranging from less than 1 m to about 7 m from the fault and correlates, in a general way, with the amount of cumulative fault offset. The width of the zone of influence around a fault does not appear to be related to depth. The amount of deformation associated with faults appears, in part, to be dependent upon which lithologic unit is involved in the faulting. Lithostratigraphic controls affect fracture spacing, type, number of fracture sets, continuity of individual fractures within each lithostratigraphic zone, and they also affect the fracture connectivity of the network as a whole. Faulting is an ongoing tectonic process at and near Yucca Mountain (Whitney 1996).

Discussion: Faulting effects on flow in the UZ are addressed through the use of a dual-permeability flow model. Changes in the hydrologic properties of existing faults are expected to be of low consequence to dose as demonstrated by the analysis presented in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMW M&O 2000e).

Faulting effects on flow in the SZ are addressed through the use of flowing intervals and consideration of existing fault zones (CRWMS M&O 2000p and 2000o). The approach used for consideration of flow in the SZ includes consideration of uncertainties about the flow-interval properties and locations. The relocation of flowing intervals in the SZ within each unit (which might result from reactivated faults or new faulting) does not affect the contaminant flux at the 20-km boundary (CRWMS M&O 2000o).

Primary FEP: Faulting (continued)

The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA (USGS 1998). The PSHA also indicates that future displacement of intrablock faults (i.e., reactivation of existing faults) will be on the order of 1 m or less, and is, therefore, not significant with regard to the physical integrity of the repository. Repository designs also include the use of 60-m set-backs from known, block-bounding faults, which have potentially significant movement if reactivated.

Therefore, changes in properties of the existing faults or reactivation of existing faults will not significantly affect radionuclide transport, and dose will be negligibly impacted. This FEP can, therefore, be *Excluded* based on low consequence to dose.

Relation of Elements of Primary FEP Description to Secondary FEPs	
Faulting occurs due to sudden major changes in the stress situation or due to tectonic activity	Faulting (1.2.02.02.01) Detachment fault occurs or exists at Yucca Mountain (1.2.02.02.10) Faulting (large-scale in geosphere) (1.2.02.02.16).
Existing fractures and faults.	Fault activation (1.2.02.02.03) Movements along small-scale faults (1.2.02.02.04) Faulting/fracturing (1.2.02.02.05) Fault movement (1.2.02.02.07) Normal faulting occurs at Yucca Mountain (1.2.02.02.08) Strike/slip faulting occurs or exists at Yucca Mountain (1.2.02.02.09) Dip/slip faulting occurs at Yucca Mountain (1.2.02.02.11) Old fault strand is reactivated at Yucca Mountain (1.2.02.02.13) Movements along major faults (1.2.02.02.15)
Alteration of rock properties or flow paths.	Faulting (1.2.02.02.01) Faulting/fracturing (1.2.02.02.05)
New faults or reactivation (e.g., extension or expansion) of existing faults	Fault generation (1.2.02.02.02) Faulting/fracturing (1.2.02.02.05) Formation of new faults (1.2.02.02.06) New fault occurs at Yucca Mountain (1.2.02.02.12) New fault strand is activated at Yucca Mountain (1.2.02.02.14)

References: Supporting documentation for the evaluation of the impact of changes of fracture apertures associated with fault zones is provided in CRWMS M&O (2000e). Fault flow characteristics in the UZ and SZ are described in CRWMS M&O (2000l), CRWMS M&O (2000o), CRWMS M&O (2000p). See also *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000q) and *Features, Events, and Processes in SZ Flow and Transport* ANL-NBS-MD-000002 (CRWMS M&O 2000r).

Primary FEP: Faulting (continued)

Links to FEPs that examine related but distinct effects and consequences

Tectonic activity, seismicity, and fracturing are all associated with faulting events. Effects on the EBS, waste package, and waste form elements from faulting and seismicity event or process not described under this Primary are examined under the following Primary FEPs:

Tectonic activity—large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Fault movement shears waste container (1.2.02.03.00)
Seismic activity (1.2.03.01.00)
Seismic vibration causes container failure (1.2.03.02.00)
Rockfall (large block) (2.1.07.01.00)
Mechanical degradation or collapse of drift (2.1.07.02.00)
Movement of containers (2.1.07.03.00)

Tectonism models supporting the preceding Primaries are consistent with those applied to volcanic activity, and are linked to the Primary FEPs "Seismicity associated with igneous activity" (1.2.03.03.00) and "Igneous activity" (1.2.04.01.00).

Links to FEPs that examine similar effects and consequences

Hydrologic response to seismic activity (1.2.10.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock (2.2.06.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults (2.2.06.02.00)
Changes in stress (due to seismic or tectonic effects) alter perched water zones (2.2.06.03.00)
Fracture flow in the unsaturated zone (2.2.07.08.00)
Water-conducting features in the saturated zone (2.2.07.13.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS1: Faults
USFIC3: Shallow Infiltration
USFIC4: Deep Percolation

Integrated Subissues / Related Subissues:

ENG2: Mechanical Disruption of Barriers / CLST1, CLST2, IA1, IA2, SDS2, SDS3, SDS4, RDTME2, RDTME3
ENG3: Quantity and Chemistry of Water Contacting the Waste Package and Waste Form / ENFE1, ENFE2, CLST1, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS2
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3, SDS4
Direct 1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, IA1, IA2, SDS4

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: Faulting

FEP Number: 1.2.02.02.01	**Originator FEP Description**: Movement between adjacent rock masses, along a fracture, could result in changes [in] hydraulic heads, groundwater flow and rock stresses. (AECL)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is construed to relate to movement along faults, and is limited to resulting changes in hydraulic heads, groundwater flow, and rock stresses. Faulting may alter the rock permeability in the rock through changes in the rock stresses; this may be reflected in changes in hydraulic heads and/or groundwater flow conditions. Faulting can, thereby, short-circuit the flow paths and flow distributions close to the repository and create new pathways through the repository.

Discussion: The impact of changes of hydrologic conditions of existing faults and fractures was evaluated in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e) through a sensitivity analysis for the effects of increased and decreased fracture aperture in fault zones. No significant change in transport characteristics was found. The approach used for consideration of flow in the SZ includes consideration of uncertainties about the flow-interval properties and locations. The relocation of flowing intervals in the SZ within each unit (which could be caused by faulting) does not effect the contaminant flux at the 20-km boundary (CRWMS M&O 2000o). Changes in hydraulic head associated with fault movements (i.e., earthquake events) have been shown by Gauthier et al. (1996) to be short-lived and of insufficient magnitude to affect repository performance. Because the effects of faulting have been shown to be of no consequence on flow, faulting does not significantly affect dose. Therefore, this FEP is of low consequence to dose

Primary FEP: Faulting
Secondary FEP: Fault generation

FEP Number: 1.2.02.02.02	**Originator FEP Description**: (none) (NEA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is non-specific and is conjectured to be concerned with the effects of the creation of new faults, or lengthening of existing 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 extension or expansion of existing faults may enhance the groundwater flow, thus decreasing the transport times for potentially released radionuclides. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and the waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA (USGS 1998). Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Consequently, there would be no mechanism for fault generation to significantly affect groundwater flow or repository integrity, and there would be no mechanism present from faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: Fault activation

FEP Number: 1.2.02.02.03	**Originator FEP Description:** (none) (NEA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: This FEP is non-specific and is conjectured to relate to effects stemming from movement along existing faults or fractures or reactivation of existing 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. The extension or expansion of existing faults may enhance the groundwater flow, thus decreasing the transport times for potentially released radionuclides. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The impact of changes of hydrologic conditions of existing faults and fractures was evaluated in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e) through a sensitivity analysis for fracture aperture. No significant change in transport characteristics was found.

The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA (USGS 1998). Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Consequently, there would be no mechanism for fault generation to significantly affect groundwater flow or repository integrity, and there would be no mechanism present for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: Movements along small-scale faults

FEP Number: 1.2.02.02.04	**Originator FEP Description**: A fraction of the deformation will be absorbed by minor faults such as the cataclastic zones intercepting emplacement tunnels. The displacement is likely to be [on] the order of a few centimeters and not exceed 1 m in one million years. etc. (NAGRA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is construed to relate to the effects of movement along small-scale (i.e., exhibiting a few meters displacement or less) existing 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. Movement along faults may enhance the groundwater flow, thus decreasing the transport times for potentially released radionuclides. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The impact of changes of hydrologic conditions of existing faults and fractures was evaluated in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e) through a sensitivity analysis for fracture aperture. No significant change in transport characteristics was found. Changes in hydraulic head associated with fault movements (i.e., earthquake events) have been shown by Gauthier et al. (1996) to be short-lived and of insufficient magnitude to affect repository performance. The approach used for consideration of flow in the SZ includes consideration of uncertainties about the flow-interval properties and locations. The relocation of flowing intervals in the SZ within each unit (which might be caused by fault movement) does not effect the contaminant flux at the 20-km boundary.

Displacements along existing faults and fractures within the repository, which might be detrimental to the physical integrity of system components, will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults.

Because groundwater flow conditions are not affected, and the magnitude of movement is insufficient to significantly affect waste package integrity, there would be no mechanism present for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: Faulting/Fracturing

FEP Number: 1.2.02.02.05	**Originator FEP Description**: Faults and fractures are the primary pathways for groundwater movement and, hence, radionuclide transport. Generation of new faults and reactivation of preexisting faults may significantly change the far-field transport paths. (UK-HMIP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low Probability of new fault and Low consequence to dose of changes in existing faults.

***Potential Consequences**:* This FEP is construed to apply to existing and new faults, and to changes that might affect far-field transport paths. For evaluation purposes, the "far-field" refers to transport in the SZ. Faulting may alter the rock permeability in the rock mass and alter or short-circuit the flow paths and flow distributions. New faults or the extension or expansion of existing faults may enhance the groundwater flow, thus decreasing the transport times for potentially released radionuclides.

Discussion: Faulting in the SZ is addressed through the use of flowing intervals and consideration of existing fault zones (CRWMS M&O 2000p and 2000o). This approach includes consideration of uncertainties about the flow-interval properties and locations. The relocation of flowing intervals within each unit does not affect the contaminant flux at the 20-km boundary (CRWMS M&O 2000o). Therefore, this FEP, as it pertains to changes in the flow system, is of low consequence to dose.

Primary FEP: Faulting
Secondary FEP: Formation of new faults

FEP Number: 1.2.02.02.06	**Originator FEP Description**: Faults are present in the Delaware Basin in both the units underlying the Salado and in the Permian evaporite sequence. [. . .] There is evidence that movement along faults within the pre Permian units affected the thickness of Early Permian strata but these faults did not exert a structural control on the deposition of the Castile, the Salado, or the Rustler. etc. (WIPP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low Probability

***Potential Consequences**:* This FEP is specific to the Waste Isolation Pilot Project (WIPP) and the associated geology. The corollary at Yucca Mountain is whether the structural controls relate to the past deposition of tuffs in a subsiding structural basin have implications for development of new faults in the vicinity of the repository.

Discussion: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Yucca Mountain is in an overall subsiding structural basin with a waning rate of subsidence (Fridrich 1999). The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The predominate form of faulting in the Yucca Mountain region is dip-slip faulting (primarily as normal faults, but reverse faults are present), and strike-slip faulting may be present as a component of normal faulting.

All of these factors, and multiple tectonic models, were evaluated to determine the probability of fault displacements along block-bounding faults and for displacements in intact rock. The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA (USGS 1998). Additionally, the tectonic setting is one of waning subsidence. Consequently, there is a low probability of the formation of new faults.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: Fault movement

FEP Number: 1.2.02.02.07	**Originator FEP Description**: Faults are present in the Delaware Basin in both the units underlying the Salado and in the Permian evaporite sequence. [. . .] There is evidence that movement along faults within the pre-Permian units affected the thickness of Early Permian strata, but these faults did not exert a structural control on the deposition of the Castile, the Salado, or the Rustler. etc. (WIPP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is specific to the Waste Isolation Pilot Project (WIPP) and the associated geology. The corollary at Yucca Mountain is whether the structural controls related to the past deposition of tuffs in a subsiding structural basin have implications for the future movement of existing faults in the vicinity of the repository.

Discussion: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Yucca Mountain is in an overall subsiding structural basin with a waning rate of subsidence (Fridrich 1999). The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The predominant form of faulting in the Yucca Mountain region is dip-slip faulting (primarily as normal faults, but reverse faults are present), and strike-slip faulting may be present as a minor component of normal faulting.

All of these factors, and multiple tectonic models, were evaluated to determine the probability of fault displacements along block-bounding faults and for displacements in the repository area. (USGS 1998). Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Consequently, there would be no mechanism for fault generation to significantly affect groundwater flow or repository integrity, and there would be no mechanism present for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: Normal faulting occurs or exists at Yucca Mountain

FEP Number: **1.2.02.02.08**	**Originator FEP Description**: Normal faulting occurs around Yucca Mtn. or normal movement on existing normal faults occurs. (YMP)
Screening Decision: *Included* in the TSPA-SR for existing fault characteristics / *Excluded* from the TSPA-SR for changes of fault characteristics.	**Screening Decision Basis**: Does not satisfy a screening criterion / Low consequence to dose.

Potential Consequences: 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. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The characteristics of existing faults are *Included* in the TSPA-SR. Faulting effects on flow in the UZ are addressed through the use of a dual-permeability flow model. Changes in the hydrologic properties of existing faults are expected to be of low consequence to dose as demonstrated by the analysis presented in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMW M&O 2000e).

Faulting effects on flow in the SZ are addressed through the use of flowing intervals and consideration of existing fault zones (CRWMS M&O 2000p and 2000o). The approach used for consideration of flow in the SZ includes consideration of uncertainties about the flow-interval properties and locations. The relocation of flowing intervals in the SZ within each unit does not effect the contaminant flux at the 20-km boundary.

The existence of normal faults at Yucca Mountain, along with multiple tectonic models, was evaluated to determine the probability of fault displacements along block-bounding faults and for displacements in intact rock. The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA (USGS 1998). Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Consequently, there would be no mechanism for normal faults to significantly affect groundwater flow or repository integrity, and there would be no mechanism present for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: Strike-slip faulting occurs or exists at Yucca Mountain

FEP Number: 1.2.02.02.09	**Originator FEP Description**: Strike/slip faulting occurs around Yucca Mtn. or strike-slip movement on existing faults occurs. (YMP)
Screening Decision: *Included* in the TSPA-SR for existing fault characteristics / *Excluded* from the TSPA-SR for changes of fault characteristics.	**Screening Decision Basis**: *Included* in the TSPA-SR Does not satisfy a screening criterion / *Excluded* from the TSPA-SR Low consequence to dose.

Potential Consequences: 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. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The characteristics of existing faults are *Included* in the TSPA. A large majority of faults at Yucca Mountain are dip-slip faults, and may exhibit some evidence of strike-slip or rotational movement.

Faulting effects on flow in the UZ are addressed through the use of a dual-permeability flow model. Faulting effects on flow in the SZ are addressed through the use of flowing intervals and consideration of existing fault zones (CRWMS M&O 2000p and 2000o).

Changes in the hydrologic properties of existing faults are expected to be of low consequence to dose as demonstrated by the analysis presented in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMW M&O 2000e). The approach used for consideration of flow in the SZ includes consideration of uncertainties about the flow-interval properties and locations. The relocation of flowing intervals in the SZ within each unit does not effect the contaminant flux at the 20-km boundary.

The potential existence of strike-slip faulting at Yucca Mountain, along with multiple tectonic models, was evaluated to determine the probability of fault displacements along block-bounding faults and for displacements in intact rock. The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA (USGS 1998). Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Consequently, there would be no mechanism for strike-slip faults to significantly affect groundwater flow or repository integrity, and there would be no mechanism present for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: Detachment faulting occurs or exists at Yucca Mountain

FEP Number: 1.2.02.02.10	**Originator FEP Description**: Detachment faulting occurs around Yucca Mtn. or movement on existing listric faults occurs. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: The concern for detachment faulting relates to deeper subsurface / tectonic-related issues as opposed to directly impacting repository performance. Movement along detachment faults may translate into seismic events and movement along normal and/or strike-slip faults present at Yucca Mountain.

Discussion: The existence of a detachment fault at Yucca Mountain is conjectural. The PSHA (USGS 1998), however, specifically considered the possibility of detachment faulting as a special case consideration, and includes the translation to seismic events and movement along normal and/or strike slip faults in the results for seismic hazard and fault-displacement hazard curves. Because of its consideration as part of the PSHA, detachment faults are of low consequence to dose.

Primary FEP: Faulting
Secondary FEP: Dip-slip faulting occurs at Yucca Mountain

FEP Number: 1.2.02.02.11	**Originator FEP Description**: Dip/slip faulting occurs around Yucca Mtn. or dip-slip movement on existing faults occurs. (YMP)
Screening Decision: *Included* in the TSPA-SR for existing fault characteristics / *Excluded* from the TSPA-SR for changes of fault characteristics.	**Screening Decision Basis**: Does not satisfy a screening criterion / Low consequence to dose.

Potential Consequences: 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. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the Engineered Barrier System (EBS) and the waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The characteristics of existing faults are *Included* in the TSPA. Faulting effects on flow in the UZ are addressed through the use of a dual-permeability flow model. Changes in the hydrologic properties of existing faults are expected to be of low consequence to dose as demonstrated by the analysis presented in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMW M&O 2000e).

Faulting effects on flow in the SZ are addressed through the use of flowing intervals and consideration of existing fault zones (CRWMS M&O 2000p and 2000o). The approach used for consideration of flow in the SZ includes consideration of uncertainties about the flow-interval properties and locations. The relocation of flowing intervals in the SZ within each unit does not effect the contaminant flux at the 20-km boundary.

The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA (USGS 1998).

Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: New fault occurs at Yucca Mountain

FEP Number: 1.2.02.02.12	**Originator FEP Description**: A new fault develops through or near Yucca Mountain. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low Probability

Potential Consequences: This FEP relates specifically to the creation 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. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA USGS 1998).

Primary FEP: Faulting
Secondary FEP: Old fault strand is reactivated at Yucca Mountain

FEP Number: 1.2.02.02.13	**Originator FEP Description**: An old fault strand (e.g., H-5 Splay of Solitario Canyon fault) through or near Yucca Mountain is reactivated. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is site-specific and is concerned with the effects stemming from movement along existing faults or fractures or reactivation of existing 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. The extension or expansion of existing faults may enhance the groundwater flow, thus decreasing the transport times for potentially released radionuclides. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The impact of changes of hydrologic conditions of existing faults and fractures was evaluated in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e) through a sensitivity analysis for fracture aperture. No significant change in transport characteristics was found.

The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA (USGS 1998). Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Consequently, there would be no mechanism for fault generation to significantly affect groundwater flow or repository integrity, and there would be no mechanism present for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: New fault strand is activated at Yucca Mountain

FEP Number: 1.2.02.02.14	**Originator FEP Description**: A new fault strand develops from an existing fault through or near Yucca Mountain (e.g., a strand off Solitario Canyon fault, in the manner of the H-5 Splay). (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP relates specifically to the creation 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. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The probability of creation of new faults in intact rock is negligible as demonstrated in the PSHA (USGS 1998). Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Consequently, there would be no mechanism for fault generation to significantly affect groundwater flow or repository integrity, and there would be no mechanism present for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting
Secondary FEP: Movements along major faults

FEP Number: 1.2.02.02.15	**Originator FEP Description**: Movements along faults will occur due to the updoming of the Southern Black Forest and the existing compressive stress field in the crystalline basement resulting from the Alpine orogeny. The relative movement along any fault will lie in the range 0 to 100 m in one million years. (NAGRA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is specific to a European site and not to Yucca Mountain. The FEP is conjectured to be concerned with the effects of movement along existing major faults (i.e., inferred to mean the Solitario Canyon or Bow Ridge faults near the repository, and block-bounding faults on a more regional sense). 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. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The impact of changes of hydrologic conditions of existing faults and fractures was evaluated in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e) through a sensitivity analysis for fracture aperture. No significant change in transport characteristics was found.

Changes in hydraulic head associated with fault movements (i.e., earthquake events) have been shown by Gauthier et al. (1996) to be short-lived and of insufficient magnitude to affect repository performance. Faulting in the SZ is addressed through the use of flowing intervals and consideration of existing fault zones (CRWMS M&O 2000p and 2000o). This approach includes consideration of uncertainties about the flow-interval properties and locations. The relocation of flowing intervals within each unit does not affect the contaminant flux at the 20-km boundary.

Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Consequently, there would be no mechanism for fault movement to significantly affect groundwater flow or repository integrity, and there would be no mechanism present for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting (continued)

Primary FEP: Faulting
Secondary FEP: Faulting (large scale, in geosphere)

FEP Number: 1.2.02.02.16	Originator FEP Description: Faulting may occur due to sudden changes in the stress situation, e.g., earthquakes, etc., and due to slow motions (creep) in the rockmass, e.g., orogenic events, loading-unloading of an ice load, and plate motions. The result is a fracture or if a movement occurs along the fracture, a fault. (Joint SKI/SKB)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is concerned with the effects of movement along existing major faults (i.e., inferred to mean the Solitario Canyon or Bow Ridge faults near the repository, and block-bounding faults in a more regional sense). 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. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Discussion: The impact of changes of hydrologic conditions of existing faults and fractures was evaluated in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e) through a sensitivity analysis for fracture aperture. No significant change in transport characteristics was found.

Changes in hydraulic head associated with fault movements (i.e., earthquake events) have been shown by Gauthier et al. (1996) to be short-lived and of insufficient magnitude to affect repository performance.

Faulting in the SZ is addressed through the use of flowing intervals and consideration of existing fault zones (CRWMS M&O 2000p and 2000o). This approach includes consideration of uncertainties about the flow-interval properties and locations. The relocation of flowing intervals within each unit does not affect the contaminant flux at the 20-km boundary (CRWMS M&O 2000o).

Displacements along existing faults and fractures within the repository will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Consequently, there would be no mechanism for fault movement to significantly affect groundwater flow or repository integrity, and there would be no mechanism present for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Faulting
Secondary FEP: Faulting exhumes waste container

FEP Number: 1.2.02.02.17	Originator FEP Description: Cumulative slip along existing faults exhumes a waste container and brings it to the surface.
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is taken from the IRSR and is conjectured to refer to movement along existing major faults (i.e., inferred to mean the Solitario Canyon or Bow Ridge faults near the repository). It specifically applies to exhumation of a waste package to the surface.

Discussion: Displacements along existing major faults, which might be detrimental to the physical integrity of system components, occur in episodic events. The cumulative displacement rate for local faults is less than 1 mm/yr, Consequently, the low movement rate precludes movement to the surface within the regulatory period of concern (10,000 years). Additionally, the repository design requires 60-m set-backs from the block-bounding faults. Consequently, there would be no mechanism for this faulting to effect waste-package integrity, and, therefore, no mechanism for faulting to significantly affect dose. Therefore, this FEP is of low consequence to dose.

Primary FEP: Fault Movement Shears Waste Container

FEP Number: 1.2.02.03.00	**Primary FEP Description:** A fault intersects the repository and a line of waste containers. That intersection shears containers by virtue of the relative offset across the containers.
Primary Assigned to: Disruptive Events FEPs, Waste Package FEPs	
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low Probability
Number of Secondaries: *None* **Screening Decision:** *Not Applicable*	

Geologic Process: Faulting

Potential Consequences: Faulting is a potentially disruptive process with effects that include earthquakes (i.e., vibratory ground motion), rock-strength failure, and sudden changes in geometry and physical properties of rock adjacent to the fault that are potentially relevant to integrity of the potential repository. Faulting, through disruption and displacement of rock mass, may also present a physical hazard to the integrity of elements of the EBS and waste packages, leading in turn to the potential for release of radionuclides.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains. Faulting is an ongoing tectonic process at and near Yucca Mountain (Whitney 1996).

Discussion: The characteristics of existing faults are *Included* in the TSPA. Displacements along existing faults, which might be detrimental to the physical integrity of system components, will either be of low magnitude (USGS 1998) or will be addressed by the use of set-backs. The probability of creation of new faults in intact rock or of significantly large movements along existing faults, is negligible as demonstrated in the PSHA (USGS 1998). The potential for disruption of the emplacement drifts through this mechanism is also analyzed in *Effects of Fault Displacement on Emplacement Drifts* (CRWMS M&O 2000s). Because the effects of fault displacement are negligible or are addressed by the repository design (in this case, set-backs), there would be no mechanism for faulting to compromise the integrity of the waste package and no resulting release of radionuclides. If no radionuclides are released, there would be no significant impact on dose, and the FEP is *Excluded* based on low consequence to dose.

Relation of Elements of Primary FEP Description to Secondary FEPs *Not Applicable*

References: Supporting documentation for the evaluation of fault displacement effects on waste container integrity and emplacement drifts is provided in CRWMS M&O (1998a) and CRWMS M&O (2000s).

Links to FEPs that examine related but distinct effects and consequences

Tectonic activity—large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Faulting (1.2.02.02.00)
Fault movement shears waste container (1.2.02.03.00)
Seismic activity (1.2.03.01.00)
Seismic vibration causes container failure (1.2.03.02.00)
Mechanical impact on waste container and drip shield (2.1.03.07.00)
Rockfall (large block) (2.1.07.01.00)
Mechanical degradation or collapse of drift (2.1.07.02.00)

Links to FEPs that examine similar effects and consequences

Movement of containers (2.1.07.03.00)
Floor buckling (2.1.07.06.00)

Primary FEP: Fault Movement Shears Waste Container (continued)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS1: Faults

Integrated Subissues / Related Subissues:

ENG2: Mechanical Disruption of Barriers / CLST2, CLST 6, IA1, IA2, SDS1, RDTME2, RDTME3

Primary FEP: Seismic Activity

FEP Number: 1.2.03.01.00	**Primary 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 stresses, and severe disruption of the integrity of the drifts (e.g., vibration damage, rockfall).
Primary Assigned to: Disruptive Events FEPs, Unsaturated Zone FEPs, Saturated Zone FEPs	
Screening Decision: *Excluded* from the TSPA-SR *(Preliminary)* for indirect effects / *Excluded* for the TSPA-SR (Preliminary) for breaching of drip shield, and of the emplacement pallet and waste package / *Included* in the TSPA-SR for fuel-rod cladding damage	**Screening Decision Basis**: Low consequence to dose / Low consequence to dose / Does not satisfy a screening criterion
Number of Secondaries: 7 **Screening Decisions**: *Excluded* from the TSPA-SR	

Geologic Process: Seismicity

Potential Consequences: Seismic activity is the result of fault slip, and both processes can cause changes in rock stresses. The change in the state of stress has the potential to affect groundwater flow-and-transport properties. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS or waste packages, leading to a release of radionuclides.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The peak phase of tectonism took place 12 to 11.6 Ma, and the region has since experienced a declining rate of extension. Stress regimes are as described by Savage et al. (1999).

Discussion: Seismic activity as it relates to the fault growth and formation is more fully addressed under the Primary FEP "Faulting" (1.2.02.02.00) and, based on the results of the PSHA (USGS 1998), has been *Excluded*.

Changes in groundwater flow are more fully addressed in the Primary FEP "Hydrologic response to seismic activity" (1.2.10.01.00), which is also *Excluded*. Changes in stress conditions are addressed in three Primary FEPs : "Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock" (2.2.06.01.00); "Changes in stress (due to thermal, seismic, or tectonic effects) produce changes in permeability of faults" (2.2.06.02.00); and "Changes in stress (due to seismic or tectonic effects) alter perched water zones "(2.2.06.03.00), all of which are *Excluded*.

The matrix- and fracture-parameter values for the hydrogeologic units and the faults are included in the analysis performed in the *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e). The analysis is based on the changing of fracture apertures. Given a change in fracture aperture, other fracture hydrologic properties (permeability, capillary pressure, and porosity) were estimated through the use of theoretical models. Although the analysis particularly addresses the effects of fault displacement, the analysis is mechanistically based only on the change of fracture apertures, regardless of the proximal cause of the change. Therefore, the analysis is potentially applicable to fracturing stemming from thermal, seismic, or tectonic events, as long as the amount of induced changes in fracture apertures are within the range of apertures evaluated in the analysis. This analysis showed that changes in fracture aperture (0.2 times to 10 times the existing fracture aperture) had minimal impact on UZ flow characteristics.

The SZ flow model addresses existing fractures through the use of flowing intervals, which are a subset of water-conducting features within the fracture system. Both the UZ and SZ flow models include fractures and uncertainty in the hydrologic-and-transport properties of the fracture system. Unless stress vectors acting on Yucca Mountain were to deviate markedly from those acting within the past few million years, the shear strength of intact rock would not be exceeded in the presence of fracture sets favorably oriented to accommodate increased stress. Because of the existing consideration of uncertainty in fracture properties and the low probability of the formation of new fractures, changes in fracture properties are not likely to significantly alter the rate of flow, significantly alter the fracture characteristics, or otherwise alter the groundwater flux through the repository. Because these factors are not significantly affected, there is no change to the dose, and the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Seismic Activity (continued)

Seismic effects on drift integrity have been considered as part of the Primary FEPs "Rockfall (large block)" (2.1.07.01.00) and "Mechanical degradation or collapse of drift" (2.1.07.02.00) and are *Excluded.* Seismic activity can also directly affect components of the EBS and waste packages through vibratory motion. This is more fully addressed in the Primary FEP "Seismic vibration causes container failure" (1.2.03.02.00), and with the exception of fuel-rod- cladding damage, has been *Excluded* (Preliminary). Because significant changes to these intermediary systems have been excluded, there is no mechanism for seismic activity to lead to an increased release of radionuclides, and dose is, therefore, not significantly affected. Consequently, this FEP is *Excluded* based on low consequence to dose.

Relation of Elements of Primary FEP Description to Secondary FEPs	
Jointed-rock motion	Earthquakes (1.2.03.01.03) Seismicity (1.2.03.01.04) Seismicity (1.2.03.01.06)
Fault growth and formation	Seismicity (1.2.03.01.06)
Changes in hydraulic heads and/or recharge or discharge zones	Earthquakes (1.3.02.01.02) Seismic activity (1.2.03.01.07)
Changes in rock stress	Seismicity (1.2.03.01.06)
Disruption of integrity of the drifts (vibration damage, rockfall)	Earthquakes (1.2.02.01.01) Seismicity (1.2.03.01.05)

References: The supporting documentation pertaining to seismicity are found in the PSHA (USGS 1998) and in *Characterize Framework for Seismicity and Structural Defomation at Yucca Mountain, Nevada* (CRWMS M&O 2000k). See also *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000q) and *Features, Events, and Processes in SZ Flow and Transport* ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Primary FEP: Seismic Activity (continued)

Links to FEPs that examine related but distinct effects and consequences

Faulting and seismicity are associated with tectonism. Effects on the EBS, waste packages, and waste-form elements from faulting or seismicity events or processes not described under this Primary are examined under the following Primary FEPs:

Tectonic activity—large scale (1.2.01.01.00)

Fractures (1.2.02.01.00)

Faulting (1.2.02.02.00)

Fault movement shears waste container (1.2.02.03.00)

Rockfall (large block) (2.1.07.01.00)

Mechanical degradation or collapse of drift (2.1.07.02.00)

Movement of containers (2.1.07.03.00)

Tectonism models supporting the preceding Primaries are consistent with those applied to volcanic activity, and are linked to the Primary FEPs "Seismicity associated with igneous activity" (1.2.03.03.00) and "Igneous activity" (1.2.04.01.00).

Links to FEPs that examine similar effects and consequences

Seismic vibration causes container failure (1.2.03.02.00)
Seismicity associated with igneous activity (1.2.03.03.00).
Hydrologic response to seismic activity (1.2.10.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock (2.2.06.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults (2.2.06.02.00)
Changes in stress (due to seismic or tectonic effects) alter perched water zones (2.2.06.03.00)
Fracture flow in the unsaturated zone (2.2.07.08.00)
Water-conducting features in the saturated zone (2.2.07.13.00)

Primary FEP: Seismic Activity (continued)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS2: Seismicity
RDTME2: Seismic Design

Integrated Subissues / Related Subissues:

ENG1: Degradation of Barriers / ENFE1, CLST1, CLST2, CLST6
ENG2: Mechanical Disruption of Barriers / SDS1, SDS3, SDS4, RDTME2, RDTME3
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS1, SDS3

Primary FEP: Seismic Activity
Secondary FEP: Earthquakes

FEP Number: 1.2.03.01.01	**Originator FEP Description:** Large earthquakes, vibration from many smaller earthquakes, or related events such as movement of the crust or plate could affect all components of the vault. (AECL)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: This FEP is construed to refer to the direct, physical impact to the repository components through ground motion. Ground motion associated with seismic events has the potential to result in disruption of the integrity of components of the EBS and waste packages, thereby affecting dose by the release of radionuclides.

Discussion: Seismic effects on drift integrity have been considered as part of the Primary FEPs "Rockfall (large scale)" (2.1.07.01.00) and "Mechanical degradation or collapse of drift" (2.1.07.02.00) and have been *Excluded*. Seismic activity can also directly affect components of the EBS and waste packages through vibratory motion. This is more fully addressed in the Primary FEP "Seismic vibration causes container failure" (1.2.03.02.00), and with the exception of fuel-rod-cladding damage, has been *Excluded* (Preliminary). Therefore, this FEP is of low consequence to dose, because direct, physical damage has been *Excluded* (Preliminary), and no mechanism from earthquakes is present that significantly increases the release of radionuclides.

Primary FEP: Seismic Activity (continued)

Primary FEP: Seismic Activity
Secondary FEP: Earthquakes

FEP Number: 1.2.03.01.02	**Originator FEP Description**: Earthquakes could influence the containment of the nuclear fuel waste by opening or closing fractures in the geosphere. This may change the discharge of contaminants from the geosphere into the biosphere. (AECL)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties, thereby affecting dose.

Discussion: Changes in groundwater flow are more fully addressed in the Primary FEP "Hydrologic response to seismic activity" (1.2.10.01.00), which is also *Excluded*. Changes in stress conditions are addressed in three Primary FEPs: "Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock" (2.2.06.01.00); "Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults" (2.2.06.02.00)', and "Changes in stress (due to seismic or tectonic effects) alter perched water zones" (2.2.06.03.00), and are Excluded in all instances.

The matrix-and fracture-parameter values for the hydrogeologic units and the faults were included in the analysis performed in the *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e). This analysis showed that changes in fracture aperture (0.2 times to 10 times the existing fracture aperture) had minimal impact on UZ flow characteristics. The SZ flow model addresses existing fractures through the use of flowing intervals, which are a subset of water-conducting features within the fracture system. Both the UZ and SZ flow models include fractures and uncertainty in the hydrologic-and-transport properties of the fracture system. Unless stress vectors acting on Yucca Mountain were to deviate markedly from those acting within the past few million years, the shear strength of intact rock would not be exceeded in the presence of fracture sets favorably oriented to accommodate increased stress. Because of the existing consideration of uncertainty in fracture properties and the low probability of the formation of new fractures, changes in fracture properties are not likely to significantly alter the rate of flow, significantly alter the fracture characteristics, or otherwise alter the groundwater flux through the repository, and are, therefore, of low consequence to dose.

Primary FEP: Seismic Activity
Secondary FEP: Earthquakes

FEP Number: 1.2.03.01.03	**Originator FEP Description**: Earthquakes occur in Sweden. They are usually small, magnitude 0-4, but there are historic examples with earthquakes up to magnitude 6. etc. (Joint SKI/SKB)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Based primarily on the statement of the magnitude of various-size earthquakes, this FEP is construed to relate to rock motion. Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties, thereby affecting dose. Ground motion associated with seismic events has the potential to disrupt the integrity of components of the EBS and waste packages.

Discussion: The magnitude of earthquakes considered are specified in the PSHA (USGS 1998) and in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (CRWMS M&O 2000k). The ground motion and fault-displacement hazards are based on this information, and are used in the analysis of seismic-vibration considerations. With the exception of fuel-rod-cladding damage, seismic vibration is of low consequence to dose.

Primary FEP: Seismic Activity (continued)

Primary FEP: Seismic Activity
Secondary FEP: Seismicity

FEP Number: 1.2.03.01.04	**Originator FEP Description**: (none) (NEA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is construed to be identical in intent to the Primary description. Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties, thereby affecting dose. Ground motion associated with seismic events has the potential to disrupt the integrity of components of the EBS and waste packages.

Discussion: See discussion for the Primary

Primary FEP: Seismic Activity
Secondary FEP: Seismicity

FEP Number: 1.2.03.01.05	**Originator FEP Description**: Seismic activity is low in the potential repository siting areas in Northern Switzerland, and the corresponding risk to safety is considered negligible. Direct disturbance of a sealed repository by seismic activity can practically be ruled out. etc. (NAGRA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is specific to a site in Switzerland. It is construed to refer to consideration of the potential, physical impact to the repository components through ground motion. Ground motion associated with seismic events has the potential to result in disruption of the integrity of components of the EBS and waste packages, thereby affecting dose by increasing the release of radionuclides.

Discussion: Seismic effects on drift integrity have been considered as part of the Primary FEPs "Rockfall (large scale)" (2.1.07.01.00) and "Mechanical degradation or collapse of drift" (2.1.07.02.00) and has been *Excluded*. Seismic activity can also directly affect components of the EBS and waste packages through vibratory motion. This is more fully addressed in the Primary FEP "Seismic vibration causes container failure" (1.2.03.02.00), and with the exception of fuel-rod-cladding damage, has been *Excluded*. Therefore, this FEP is of low consequence to dose, because direct, physical damage has been *Excluded*, and no mechanism from seismicity is present that significantly increases the release of radionuclides.

Primary FEP: Seismic Activity
Secondary FEP: Seismicity

FEP Number: 1.2.03.01.06	**Originator FEP Description**: Seismicity is the compressional and shear wave energy transmitted through the rock mass resulting naturally from the generation or reactivation of faults; it may also be induced due to stress-relief mechanisms in the near-field. (UK-HMIP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Seismic activity has the potential to result in movement along faults, resulting in changes in groundwater flow-and-transport properties, thereby affecting dose. Ground motion associated with seismic events has the potential to disrupt the integrity of components of the EBS and waste packages.

Discussion: The potential for fault growth and formation is more fully addressed under the Primary FEP "Faulting" (1.2.02.02.00) and, based on the results of the PSHA (USGS 1998), has been *Excluded*.

Primary FEP: Seismic Activity (continued)

Primary FEP: Seismic Activity
Secondary FEP: Seismic activity

FEP Number: **1.2.03.01.07**	**Originator FEP Description:** This FEP is concerned with the effects of seismic activity away from the immediate source region, and only the effects of groundshine and earthquakes are discussed. [A lengthy discussion of seismic hazards follows.] (WIPP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties and, thereby, affect dose. Ground motion associated with seismic events has the potential to disrupt the integrity of components of the EBS and waste packages.

Discussion: The magnitude of earthquakes considered is specified in the PSHA (USGS 1998) and in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (CRWMS M&O 2000k). Ground-motion and fault-displacement hazards used for seismic analysis are based on the PSHA (USGS 1998). With the exception of fuel-rod-cladding damage, seismic vibration is of low consequence to dose.

Primary FEP: Seismic Vibration Causes Container Failure

FEP Number: 1.2.03.02.00	**Primary FEP Description:** Seismic activity causes repeated vibration of container and/or container-rock wall contact, damaging the container and its contents.
Primary Assigned to: Disruptive Events FEPs, Waste Package FEPs	
Screening Decision: *Excluded* from the TSPA-SR *(Preliminary) / Included* in the TSPA-SR for fuel rod cladding damage	**Screening Decision Basis:** Low consequence to dose / Does not satisfy a screening criterion
Number of Secondaries: *1* **Screening Decision:** All *Excluded* from the TSPA-SR	

Geologic Process: Seismicity

Potential Consequences: Repeated vibration of the container, the container contents, and/or container impact causes the container to be breached. The concern with ground motion is also construed to include concerns with damage to the drip shield. Ground motion associated with seismic activity has the potential to disrupt the integrity of components of the EBS and waste packages. These processes could lead to impaired container performance and/or to radionuclide release.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The peak phase of tectonism took place 12 to 11.6 Ma, and the region has since experienced a declining rate of extension. The faults closest to Yucca Mountain are the most important to vibratory motion.

Discussion: Seismic damage to the drip shield and waste package would most likely result from mechanical impacts due to rockfalls or other mechanical impacts. Based on the analysis related to the Primary FEP "Rockfall (large scale)" (2.1.07.01.00), it is not credible to presume that the drip shield would be ruptured by mechanical impacts, and it will, therefore, protect the waste package from rockfall during seismic episodes. A likely failure mechanism for the waste package would involve becoming detached from the emplacement pallet and collision with another waste package, or collision with the drip shield. Design criteria for the uncanistered, spent-nuclear-fuel waste packages indicate that the packages must be able to withstand a 6-Metric Ton rockfall event (CRWMW M&O 2000w, Criterion 1.2.2.1.1), withstand a vertical drop of 2 m in the vertical position, and a drop of 2.4 m in the horizontal position. (CRWMS M&O 2000v). On a qualitative basis, it would appear that breaching of the waste packages by impact is not credible.

An associated damage mechanism, stemming from impacts, is increased stress cracking and corrosion, leading to potentially increased seepage through the drip shield and/or into the waste package. The major corrosive processes are stress-corrosion cracking in the welded lids of the waste package and general corrosion of both the drip shield and the waste package. Degradation of the drip shield and waste containers is being evaluated through the WAPDEG analysis, which focuses on the drip 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. Damage to drip shields or waste packages by ground motion would be of little or no consequence unless located below a drip in the emplacement drift and the water reaches the waste package. 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 and with or without seismic damage, and this is addressed for the nominal case of the TSPA-SR.

The TSPA-SR does, however, address seismic damage to fuel-rod cladding by presuming an initial breaching of the fuel-rod cladding resulting from ground motion corresponding to a 10^{-6} annual-exceedance probability, followed by "unzipping" of the cladding. Based on the analyses presented in CRWMS M&O (1999d), ground motion with a frequency of 1.1×10^{-6} annual-exceedance probability would break most of the fuel-rod cladding. Such events are *Included* as part of the TSPA-SR. When such an event occurs, all cladding is presumed failed and is considered to be subject to unzipping, rendering the radionuclides available for transport by seepage into and out of the waste package. Fuel-rod-cladding damage in *Included* in the TSPA.

Because waste-package degradation is currently *Included* in the TSPA-SR nominal case, fuel-rod-cladding damage associated with ground motion is considered, and because the ground-motion-of-concern is infrequent (i.e., less than 10^{-5} annual-exceedance probability), seismic damage to the drip shield and waste packages is not likely to contribute significantly as a risk factor and is, therefore, *Excluded* based on low consequence to dose.

Primary FEP: Seismic Vibration Causes Container Failure (continued)

Relation of Elements of Primary FEP Description to Secondary FEPs	
Repeated vibration of container	Container failure induced by microseisms associated with dike emplacement (1.2.03.02.01)
Container-rock wall contact damages container and its content	Container failure induced by microseisms associated with dike emplacement (1.2.03.02.01)

References: Background information on the geologic and seismic character of Yucca Mountain is available in the PSHA (USGS 1998) and in CRWMS M&O (2000k). Supporting documentation for the evaluation of ground motion and the effects of seismic vibration on containers is found in (CRWMS M&O 1999d and CRWMS M&O 2000f). See also: *FEPs Screening of Process and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 (CRWMS M&O 2000g); *EBS Radionuclide Transport Abstraction* ANL-WIS-PA-000001 (CRWMS M&O 2000h); *Breakage of Commercial Spent Nuclear Fuel Cladding by Mechanical Loading* CAL-EBS-MD-000001 (CRWMS M&O 1999d); *WAPDEG Analysis of Waste Package and Drip Shield Degradation* ANL-EBS-PA-000001 (CRWMS M&O 2000y)

Links to FEPs that examine related but distinct effects and consequence

Faulting and seismicity are associated with tectonism. Effects on the EBS, waste package and waste form elements from faulting, ground motion or processes not described under this Primary are examined under the following Primary FEPs:
Tectonic activity—large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Faulting (1.2.02.02.00)
Fault movement shears waste container (1.2.02.03.00)
Rockfall (large block) (2.1.07.01.00)
Mechanical degradation or collapse of drift (2.1.07.02.00)
Tectonism models supporting the preceding Primaries are consistent with those applied to volcanic activity, and are linked to the Primary FEPs "Seismicity associated with igneous activity" (1.2.03.03.00) and "Igneous activity" (1.2.04.01.00).

Links to FEPs that examine similar effects and consequences
Cladding unzipping (2.1.02.23.00)
Mechanical failure of cladding (2.1.02.24.00)
Stress corrosion cracking of waste containers and drip shields (2.1.03.02.00)
Mechanical impact on waste container and drip shield (2.1.03.07.00)
Movement of containers (2.1.07.03.00)

Links to IRSRs:

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS2: Seismicity
RDTME2: Seismic Design

Integrated Subissues / Related Subissues

ENG1: Degradation of Barriers / TEF3, ENFE1, CLST1, CLST2, CLST6
ENG2: Mechanical Disruption of Barriers / SDS1, SDS3, SDS4, RDTME2, RDTME3
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS1, SDS3

Primary FEP: Seismic Vibration Causes Container Failure (continued)

Primary FEP: Seismic Vibration Causes Container Failure
Secondary FEP: Container failure induced by microseisms associated with dike emplacement

FEP Number: **1.2.03.02.01**	**Originator FEP Description:** Seismic activity associated with dike emplacement causes repeated container-rock wall contact, damaging the container and its contents. This FEP was directed at emplacement in vertical boreholes in the drift floors. Separation of container from the rock was a centimeter or so. Vibration could cause contact. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

***Potential Consequences**:* This FEP was based on an outdated design that called for emplacing waste packages in vertical boreholes below the drift floor. The concepts of vibratory motions and/or contact with other elements of the Engineered Barrier System (EBS) or other waste packages was considered to be applicable, and consequence would be the same as those discussed for the Primary FEP.

***Discussion**:* See the Primary FEP.

Primary FEP: Seismicity Associated with Igneous Activity

FEP Number: 1.2.03.03.00	Primary FEP Description: Seismicity associated with future igneous activity in the Yucca Mountain region may affect repository performance.
Primary Assigned to: *Disruptive Events FEPs*	
Screening Decision: *Excluded* from the TSPA-SR for indirect effects / *Included* in the TSPA-SR for fuel-rod-cladding damage	**Screening Decision Basis**: Low consequence to dose / Does not satisfy a screening criterion
Number of Secondaries: *None* **Screening Decisions**: *Not Applicable*	

Geologic Process: Seismicity / Igneous Activity

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The peak phase of tectonism took place 12. to 11.6 Ma, and the region has since experienced a declining rate of extension. Several Quaternary basaltic volcanoes exist within 20 km of the Yucca Mountain repository, and future igneous activity in the region is of potential concern

Potential Consequences: Volcanic eruption is commonly preceded and accompanied by swarms of earthquakes. Basaltic volcanism within 15-20 km of Yucca Mountain could produce earthquakes sufficient to produce ground motion at the repository. Repeated vibration of container and/or container impact has the potential to cause the containers to be breached. Ground motion associated with seismic events has the potential to disrupt the integrity of components of the EBS and waste packages. These could lead to impaired performance and/or to radionuclide release.

Discussion: 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 magnitudes of earthquakes are typically less than those considered in seismic analysis.

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 (CRWMS M&O 2000k, Table 5). Volcanic-related earthquakes were not modeled as a separate source zone by the four other PSHA expert teams, under the presumption 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-SR identically to general seismic activity. Indirect effects are *Excluded* from the TSPA-SR based on low consequence to dose. Damage to fuel-rod cladding is *Included* in the TSPA-SR.

Relation of Elements of Primary FEP Description to Secondary FEPs: *Not Applicable*

References: Supporting documentation for the evaluation of seismic vibration on containers is found in (CRWMS M&O 1999d and CRWMS M&O 2000f). Background information on the geologic and seismic character of Yucca Mountain are available in the PSHA (USGS 1998) and in CRWMS M&O (2000k).

Primary FEP: Seismicity Associated with Igneous Activity (continued)

Links to FEPs that examine related but distinct effects and consequence

Faulting, seismicity, and igneous activity are associated with tectonism. Effects on the EBS, waste package, and waste-form elements from processes not described under this Primary are examined under the following Primary FEPs:

Tectonic activity—large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Faulting (1.2.02.02.00)
Fault movement shears waste container (1.2.02.03.00)
Igneous activity (1.2.04.01.00)
Rockfall (large block) (2.1.07.01.00)
Mechanical degradation or collapse of drift (2.1.07.02.00)

Tectonism models supporting the preceding Primaries are consistent with those applied to volcanic activity and are linked to the Primary FEPs "Seismicity associated with igneous activity" (1.2.03.03.00) and "Igneous activity" (1.2.04.01.00).

Links to FEPs that examine similar effects and consequences

Seismic activity (1.2.03.01.00)
Seismic vibration causes container failure (1.2.03.02.00)
Cladding unzipping (2.1.02.23.00)
Mechanical failure of cladding (2.1.02.24.00)
Stress corrosion cracking of waste containers and drip shields (2.1.03.02.00)
Mechanical impact on waste container and drip shield (2.1.03.07.00)
Movement of containers (2.1.07.03.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS2: Seismicity
IA2: Igneous Activity—Consequences

Integrated Subissues / Related Subissues:

ENG1: Degradation of Barriers / TEF3, ENFE1, CLST1, CLST6
ENG2: Mechanical Disruption of Barriers / SDS1, SDS3, SDS4, RDTME2, RDTME3
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS2
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS1, SDS2, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS1, SDS2, SDS3
Direct1: Volcanic Disruption of Waste Packages: IA1, SDS1

Primary FEP: Igneous Activity

FEP Number: 1.2.04.01.00	**Primary 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.
Primary Assigned to: Disruptive Events FEPs	
Screening Decision: *Included* in the TSPA-SR for direct effects, *Excluded* from the TSPA-SR for indirect effects	**Screening Decision Basis:** Does not satisfy a screening criterion / Low consequence to dose
Number of Secondaries: *5* **Screening Decision:** *Included* in the TSPA-SR for direct effects, *Excluded from the* TSPA-SR for indirect effects	

Geologic Process: Igneous activity, including both intrusive and eruptive processes.

Potential Consequences: Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose. The elements of the EBS and waste packages could be damaged due to severe perturbation of the drifts, thereby resulting in the release of radionuclides, thereby affecting dose.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Several Quaternary basaltic volcanoes exist within 20 km of the Yucca Mountain repository, and future igneous activity in the region is of potential concern, although the probability of intersection with the repository is only marginally greater than 1×10^{-8}.

Discussion: 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 *Included* in the TSPA-SR. The treatment of these events is discussed in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m) and is also addressed in *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa).

As discussed for the FEPs "Fractures" (1.2.02.02.00) and "Faults" (1.2.02.03.00), activation and sealing of faults have been *Excluded* due to low consequence to dose. Creation of faults or fractures was *Excluded* from the TSPA-SR based on the low probability of formation of new faults in intact rock due to seismic stresses. It can be inferred that stresses from an igneous event are more likely to affect pre-existing fractures and faults than intact rock. Additionally, as discussed for the FEP "Hydrologic response to igneous activity" (1.2.10.02.00), the orientation of intruding dikes and the fracturing along the edges of the dikes suggest that impact to flow will be minimal. Stresses related to igneous activity will act to change (either increase or decrease) fracture aperture in faults zones (i.e., sealing of faults). Change in rock stress was used in the analysis for *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000e) and both increases and decreases in fracture aperture (10 time to 0.2 time the existing fracture aperture) were shown to have minimal effect of UZ flow and transport. Because igneous activity results in minimal change to the flow system, dose is not affected, and this aspect of the FEP is *Excluded* based on low consequence to dose.

Significant changes in topography by volcanic activity are *Excluded* from the TSPA-SR due to low consequence to dose. 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. (CRWMS M&O 2000n, Section 6.2 and Table 4). Small volcanic features may have local effects on infiltration (and, hence, flow and transport) 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, *Excluded* from the TSPA-SR.

Deformation of rock will cause changes in rock stress that could either increase or decrease fracture apertures. Changes in rock stress were used in the analysis for *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000e). Both increases (10 times) and decreases (0.2 time) in fracture aperture were shown to have no consequence. Changes in rock stress and rock deformation are further discussed in the FEP "Igneous activity causes changes to rock properties" (1.2.04.02.00) and are *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Igneous Activity

The effects of changes in groundwater temperature (as reflected by hydrothermally driven mass transfer) are discussed in the FEP "Hydrologic response to igneous activity" (1.2.10.02.00), and are *Excluded* from the TSPA-SR based on low consequence to dose. 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. 1998, pp. 5-1 and 5-2).

Because the indirect effects of igneous activity (as listed in the Primary FEP description) do not create a significant change in flow, there is no mechanism for igneous activity to significantly change the dose. Consequently, the indirect effects listed in the Primary FEP Description above are *Excluded* from the TSPA-SR based on low consequence to dose.

Relation of Elements of Primary Description to Secondary FEPs	
Activation, creation, sealing of faults;	Volcanism (1.2.01.01.01) Magmatic activity (1.2.04.01.03)
Changes in topography	Volcanism (1.2.01.01.01) Volcanic activity (1.2.04.01.05)
Changes in rock stress	Volcanism (1.2.01.01.01)
Deformation of rock	Volcanism (1.2.01.01.01)
Changes in groundwater temperatures	Volcanism (1.2.01.01.01) Volcanic activity (1.2.04.01.05)
Severe perturbation to integrity of the drifts	Volcanism (1.2.01.01.01) Magmatic activity (1.2.04.01.02) Magmatic activity (1.2.04.01.03) Magmatic activity (1.2.04.01.04) Volcanic activity (1.2.04.01.05)

References: Supporting documentation for igneous processes are found in multiple documents, including: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m); *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n); *Waste Package Behavior in Magma* CAL-EBS-ME-000002 (CRWMS M&O 1999e); *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z); *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa).

Links to FEPs that examine related but distinct effects and consequences

Tectonic activity—large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Faulting (1.2.02.02.00)
Seismicity associated with igneous activity (1.2.03.03.00)

Links to FEPs that examine similar effects and consequences

Igneous activity causes changes to rock properties (1.2.04.02.00)
Igneous intrusion into repository (1.2.04.03.00)
Magma interacts with waste (1.2.04.04.00)
Magmatic transport of waste (1.2.04.05.00)
Basaltic cinder cone erupts through the repository (1.2.04.06.00)
Ashfall (1.2.04.07.00)
Hydrologic response to igneous activity (1.2.10.02.00)

Primary FEP: Igneous Activity (continued)

Links to IRSRs

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
IA1: Igneous Activity—Probability
IA2: Igneous Activity—Consequence

Integrated Subissues / Related Subissues:

ENG2: Mechanical Disruption of Barriers / CLST1, CLST2, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3
Direct 1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, SDS1, SDS4

Primary FEP: Igneous Activity
Secondary FEP: Volcanism

FEP Number: **1.2.04.01.01**	**Originator FEP Description:** Volcanism (hot spots and rifts) 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 vault. (AECL)
Screening Decision: *Included* in the TSPA-SR for direct effects, *Excluded* from the TSPA-SR for indirect effects	**Screening Decision Basis:** Does not satisfy a screening criterion / Low consequence to dose

***Potential Consequences**:* Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose, and/or the elements of the EBS and waste packages could be damaged due to severe perturbation of the drifts resulting in the release of radionuclides, thereby affecting dose.

***Discussion**:* The Secondary FEP description is nearly identical to the Primary Description. See Primary discussion.

Primary FEP: Igneous Activity (continued)

Primary FEP: **Igneous Activity**
Secondary FEP: Magmatic activity

FEP Number: **1.2.04.01.02**	**Originator FEP Description:** (none) (NEA)
Screening Decision: *Included* in the TSPA-SR for direct effects, *Excluded* from the TSPA-SR for indirect effects	**Screening Decision Basis:** Does not satisfy a screening criterion / Low consequence to dose

Potential Consequences: Due to the lack of a description, this FEP was conjectured to be synonymous with the Primary Description. Igneous activity could potentially alter the hydrologic characteristics of the site and, thereby, affect flow-and-transport characteristics and affect dose, and/or the elements of the EBS and waste packages could be damaged due to severe perturbation of the drifts resulting in the release of radionuclides, thereby affecting dose.

Discussion: See Primary discussion

Primary FEP: Igneous Activity (continued)

Primary FEP: Igneous Activity
Secondary FEP: Magmatic activity

FEP Number: **1.2.04.01.03**	**Originator FEP Description:** Magmatic activity in the repository region could have a major impact on the system. For example, a magma dike intersecting the repository could force molten rock along zones of weakness created by the disposal tunnels and associated excavation-disturbed zones; severe alteration and disturbance of the bentonite buffer would result. (NAGRA)
Screening Decision: *Included* in the TSPA-SR for direct effects	**Screening Decision Basis:** Does not satisfy a screening criterion

Potential Consequences: This FEP addresses direct disruption of the repository system, including the drifts, elements of the EBS, and waste packages and does not to apply to indirect effects. Magmatic activity could compromise the elements of the EBS and waste packages due to severe perturbation of the drifts. This has the potential to result in the release of radionuclides, thereby affecting dose.

Discussion: 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 *Included* in the TSPA-SR. The treatment of these events in the TSPA-SR is discussed in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

Primary FEP: Igneous Activity
Secondary FEP: Magmatic activity

FEP Number: **1.2.04.01.04**	**Originator FEP Description:** The occurrence of igneous activity in the form of volcanoes and associated magmatic activity would severely affect the behavior and safety of a repository. (UK-HMIP)
Screening Decision: *Included* in the TSPA-SR for direct effects, *Excluded* from the TSPA-SR for indirect effects	**Screening Decision Basis:** Does not satisfy a screening criterion / Low consequence to dose

Potential Consequences: This FEP addresses direct disruption of the repository system, including the drifts, elements of the EBS, and waste packages, and does not to apply to indirect effects. Magmatic activity could compromise the elements of the EBS and waste packages due to severe perturbation of the drifts. This has the potential to result in the release of radionuclides, thereby affecting dose.

Discussion: See Primary discussion

Primary FEP: Igneous Activity (continued)

Primary FEP: Igneous Activity
Secondary FEP: Volcanic activity

FEP Number: **1.2.04.01.05**	**Originator FEP Description:** The Paleozoic and younger stratigraphic sequences within the Delaware Basin are devoid of locally derived volcanic rocks. etc. (WIPP)	
Screening Decision: *Included* in the TSPA-SR for direct effects, *Excluded* from the TSPA-SR for indirect effects	**Screening Decision Basis:** Does not satisfy a screening criterion / Low consequence to dose	

Potential Consequences: This FEP was construed to mean that the existence of volcanic materials in the Yucca Mountain region must be considered with regard to the geologic setting and with regard to potential for future igneous activity.

Discussion: Supporting documentation for the igneous processes considered for the TSPA-SR is found in multiple documents, including: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m); *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n); and *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL - MGR-GS-000002 (CRWMS M&O 2000z).

Primary FEP: Igneous Activity Causes Changes to Rock Properties

FEP Number: 1.2.04.02.00	**Primary 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 to contaminants.
Primary Assigned to: Disruptive Events FEPs, Unsaturated Zone FEPs, Saturated Zone FEPs	
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose
Number of Secondaries: 7 **Screening Decisions:** All *Excluded* from the TSPA-SR	

Geologic Process: Igneous activity, including both intrusive and eruptive processes.

Potential Consequences: Igneous activity could potentially alter the hydrologic characteristics and has the potential to cause alteration of contaminant-retarding minerals (e.g., zeolites) in the vicinity of the igneous activity. These changes could affect flow-and-transport characteristics and affecting dose. The elements of the EBS and waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and premature failures, thereby resulting in the release of radionuclides, and consequently affect dose.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Several Quaternary basaltic volcanoes exist within 20 km of the Yucca Mountain repository, and future igneous activity in the region is of potential concern, although the probability of intersection with the repository is only marginally greater than 1×10^{-8}.

Discussion: 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.

The effects of igneous activity on the UZ are discussed more fully in *Features, Events and Processes in UZ Flow and Transport* (CRWMS M&O 2000q, Sections 6.7.7). Formation of perched water in the UZ above the repository by igneous intrusion could theoretically result in focused flow in the vicinity of the drifts. Focused flow is addressed in the TSPA-SR indirectly through the seepage-model abstraction.

The margins of dikes are associated with near-vertical jointing (Valentine et al. 1998, p. 5-32), and future dikes are likely to be oriented parallel to the direction of prevailing anisotropic transmissivity in the SZ that exists in the vicinity of Yucca Mountain (CRWMS M&O 2000z) and consistent with existing fault and fracture orientation (Ferrill, Winterle et al. 1999, p. 1). Because of the parallel orientation of dikes with the existing orientation of the anisotropic maximum horizontal permeability in the SZ, it is problematic that a dike would form a barrier or impoundment in the UZ or SZ. Furthermore, the TSPA-VA evaluation for disruptive events (CRWMS M&O 1998c, Section 10.5.3) suggests that changes in the SZ due to an intrusion of a dike would have negligible impact on repository performance.

Mineral alterations resulting from igneous activity could change the chemical response to contaminants. However, based on natural-analogue and preliminary modeling studies, the zones of alteration and hydrothermal effects around dikes are extremely limited (Valentine et al. 1998, pp. 5-41, 5-46, 5-57, and 5-74). This suggests that little destruction of sorptive minerals or hydrothermal effects is expected. Given the limited area of alteration around the intrusion, the effect of alteration on radionuclide-transport characteristics of the host rock would be negligible, and the consequence to dose is also negligible. The FEP is, therefore, *Excluded* from the TSPA-SR. The development of hydrothermal systems from igneous activity is also expected to be minimal and to not significantly affect groundwater-flow patterns. Because groundwater flow over a large area (respective to the repository) is not affected, the dose is not expected to be affected, and hydrothermal effects are, therefore, *Excluded* from the TSPA-SR based on low consequence to dose.

Because each component in the FEP description has been determined to be *Excluded* from the TSPA-SR based on low consequence to dose, this FEP is also *Excluded* from the TSPA-SR based on low consequence to dose. See also "Hydrologic response to igneous activity" (1.2.10.02.00) for additional discussions.

Primary FEP: Igneous Activity Causes Changes to Rock Properties (continued)

Relation of Elements of the Primary FEP Description to Secondary FEPs	
Extreme changes to rock hydrologic and mineralogic properties	Volcanic activity in the vicinity produces an impoundment (1.2.04.02.03) Intrusion (magmatic) (1.2.04.02.05) Magmatic activity (1.2.04.02.07)
Permeabilities of dikes and sills and the heated regions can differ from those of the country rock	Dike provides a permeable flow path (1.2.04.02.01) Dike provides a barrier to flow (1.2.04.02.02) Dike related fractures alter flow (1.2.04.02.06)
Mineral alterations can also change the geochemical response to the contaminants	Igneous activity causes extreme changes to rock geochemical properties (1.2.04.02.04)

References: Supporting documentation for igneous processes is found in multiple documents, including: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m), *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n), *Waste Package Behavior in Magma* CAL-EBS-ME-000002 (CRWMS M&O 1999e), *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z), *Dike Propagation Near Drifts* CRWMS M&O 2000aa). Studies of natural analogue sites are provided in "Physical Processes of Magmatism and Effects on the Potential Repository: Synthesis of Technical Work through fiscal year 1995" by Valentine et al. (1998).

Links to FEPs that examine related but distinct effects and consequences

Fractures (1.2.02.01.00)
Rind (altered zone) formation in waste, EBS, and adjacent rock (2.1.09.12.00)
Excavation and construction-related changes in the adjacent host rock (2.2.01.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock (2.2.06.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults (2.2.06.02.00)
Changes in stress (due to seismic or tectonic effects) alter perched water zones (2.2.06.03.00)
Groundwater chemistry/composition in UZ and SZ (2.2.08.01.00)
Geochemical interactions in geosphere (dissolution, precipitation, weathering) and effects on radionuclide transport (2.2.08.03.00)
Thermo-mechanical alteration of rocks above and below the repository (2.2.10.05.00)
Thermo-chemical alteration (solubility, speciation, phase changes, precipitation/dissolution) (2.2.10.06.00)

Links to FEPs that examine similar effects and consequences

Hydrothermal activity (1.2.06.00.00)
Thermal and other waste and EBS-related changes in the adjacent host rock (2.2.01.02.00)
Rock properties of host rock and other units (2.2.03.02.00)

Primary FEP: Igneous Activity Causes Changes to Rock Properties (continued)

Links to IRSRs

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
IA1: Igneous Activity—Probability
IA2: Igneous Activity—Consequence

Integrated Subissues / Related Subissues:

UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
UZ3 Geo: Radionuclide Transport in the UZ / ENFE1
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3
SZ2 Geo: Radionuclide Transport in the SZ / USFIC6

Primary FEP: Igneous Activity Causes Changes to Rock Properties
Secondary FEP: Dike provides a permeable flow path.

FEP Number: 1.2.04.02.01	Originator FEP Description: A new dike develops well-connected cooling fractures and is more permeable than the surrounding rock. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose. The elements of the EBS and waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and premature failures, thereby resulting in the release of radionuclides and, consequently, affect dose.

Discussion: The margins of dikes are associated with near-vertical jointing (Valentine et al. 1998, p. 5-32), and future dikes are likely to be oriented parallel to the direction of existing anisotropic transmissivity in the SZ that exists in the vicinity of Yucca Mountain (CRWMS M&O 2000aa), consistent with existing fault and fracture orientation (Ferrill, Winterle et al. 1999, p. 1). Because of the parallel orientation of dikes with the existing orientation of the anisotropic maximum horizontal permeability in the SZ, it is problematic that a dike would form a barrier or impoundment in the SZ. Furthermore, the TSPA-VA evaluation for disruptive events (CRWMS M&O 1998c, Section 10.5.3) suggests that intrusion of a dike would have negligible impact on repository performance due to changes in flow in the SZ.

Primary FEP: Igneous Activity Causes Changes to Rock Properties (continued)

Primary FEP: Igneous Activity Causes Changes to Rock Properties
Secondary FEP: Dike provides a barrier to flow

FEP Number: 1.2.04.02.02	**Originator FEP Description:** A new dike is less permeable than the surrounding rock. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

***Potential Consequences**:* Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose. The elements of the EBS and waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and premature failures, thereby resulting in the release of radionuclides and, consequently, affect dose.

***Discussion**:* The margins of dikes are associated with near-vertical jointing (Valentine et al. 1998, p. 5-32), and future dikes are likely to be oriented parallel to the direction of existing anisotropic transmissivity that exists in the vicinity of Yucca Mountain (CRWMS M&O 2000aa), consistent with existing fault and fracture orientation (Ferrill, Winterle et al. 1999, p. 1). Because of the parallel orientation of dikes with the existing orientation of the anisotropic maximum horizontal permeability in the SZ, it is problematic that a dike would form a barrier or impoundment in the SZ. Furthermore, the TSPA-VA evaluation for disruptive events (CRWMS M&O 1998c, Section 10.5.3) suggests that intrusion of a dike would have negligible impact on repository performance due to changes in flow in the SZ.

Primary FEP: Igneous Activity Causes Changes to Rock Properties
Secondary FEP: Volcanic activity in the vicinity produces an impoundment

FEP Number: 1.2.04.02.03	**Originator FEP Description:** Volcanic activity in the vicinity of the site (e.g., lava flow) leads to damming of a wash or canyon that produces a large surface-water impoundment. Percolation flux is substantially increased beneath the impoundment and interacts with the repository. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

***Potential Consequences**:* Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose. The elements of the EBS and waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and premature failures, thereby resulting in the release of radionuclides, and consequently affect dose.

***Discussion**:* This secondary FEP is best addressed in the response to "Hydrologic response to igneous activity" (1.2.10.02.00). If lava were to dam one or more washes above the repository block, the dam would probably not produce a large surface-water impoundment. It is more likely that streams would grade by means of alluvial deposition to the lava dam spillway level within a few decades. Additionally, extruded lava would likely consist of clinker or aa (a type of lava flow typified by angular, jagged blocks), and would not form an effective dam.

Primary FEP: Igneous Activity Causes Changes to Rock Properties (continued)

Primary FEP: Igneous Activity Causes Changes to Rock Properties
Secondary FEP: Igneous activity causes extreme changes to rock geochemical properties

FEP Number: 1.2.04.02.04	Originator FEP Description: Igneous activity near the underground facility causes extreme changes to rock mineralogic properties. Mineral alterations also change the chemical response to contaminants. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose. The elements of the EBS and waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and premature failures, thereby resulting in the release of radionuclides, and consequently affect dose.

Discussion: Based on natural-analogue and preliminary modeling studies, the zones of alteration and hydrothermal effects around dikes are extremely limited (Valentine et al. 1998, pp. 5-41, 5-46, 5-57, and 5-74). This suggests that little destruction of sorptive minerals or hydrothermal effects is expected. Given the limited area of alteration around the intrusion, the effect of alteration on radionuclide-transport characteristics of the host rock would be negligible, and the consequence to dose is also negligible. The FEP is, therefore, *Excluded* from the TSPA-SR. The development of hydrothermal systems from igneous activity is also expected to be minimal and to not significantly affect groundwater-flow patterns. Because groundwater flow over a large area (respective to the repository) is not affected, the dose is not expected to be affected, and hydrothermal effects are, therefore, *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Igneous Activity Causes Changes to Rock Properties
Secondary FEP: Intrusion (magmatic)

FEP Number: 1.2.04.02.05	Originator FEP Description: Magmatism near the disposal facility could lead to substantial changes in existing groundwater flows and rock properties. (AECL)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: This FEP was construed to be similar to the Primary FEP Description but limited to the aspect of "substantial" changes. Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose. The elements of the EBS and waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and premature failures, thereby resulting in the release of radionuclides, and consequently affect dose.

Discussion: See discussion for Primary FEP.

Primary FEP: Igneous Activity Causes Changes to Rock Properties (continued)

Primary FEP: Igneous Activity Causes Changes to Rock Properties
Secondary FEP: Dike-related fractures alter flow

FEP Number: **1.2.04.02.06**	**Originator FEP Description:** The intrusion, either by emplacement or during cooling, can produce a set of fractures in a zone adjacent to the dike, altering flow characteristics. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose. The elements of the EBS and waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and premature failures, thereby resulting in the release of radionuclides and, consequently, affect dose.

Discussion: The margins of dikes are associated with near-vertical jointing (Valentine et al. 1998, p. 5-32), and future dikes are likely to be oriented parallel to the direction of existing anisotropic transmissivity in the SZ that exists in the vicinity of Yucca Mountain (CRWMS M&O 2000aa), consistent with existing fault and fracture orientation (Ferrill, Winterle et al. 1999, p. 1). Because of the parallel orientation of dikes with the existing orientation of the anisotropic maximum horizontal permeability in the SZ, 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 1998c, Section 10.5.3) suggests that intrusion of a dike would have negligible impact on repository performance due to changes in flow in the SZ.

Primary FEP: Igneous Activity Causes Changes to Rock Properties
Secondary FEP: Magmatic activity

FEP Number: **1.2.04.02.07**	**Originator FEP Description:** Magmatism could occur in the vicinity of the vault, leading to substantial changes to groundwater flow and rock properties. (AECL)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: This FEP was construed to be identical to the Primary FEP Description. Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose. The elements of the EBS and waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and premature failures, thereby resulting in the release of radionuclides and, consequently, affect dose.

Discussion: See discussion for Primary FEP.

Primary FEP: Igneous Intrusion Into the Repository

FEP Number: **1.2.04.03.00**	**Primary FEP Description:** Magma from an igneous intrusion flows into the drifts and extends over a 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.
Primary Assigned to: Disruptive Events FEPs, Waste Package FEPs	
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion
Number of Secondaries: 5 **Screening Decisions:** All *Included* in the TSPA-SR	

Geologic Process: Igneous activity, including both intrusive and eruptive processes.

Potential Consequences: The elements of the EBS and waste packages could be damaged due to severe perturbation of the drifts, thereby resulting in the release of radionuclides, and affecting dose. The type of intrusion in the FEP description is shown as a sill (a horizontal tabular body). Intersection of the repository by a dike (a vertical tabular body) is a more feasible initiating event, followed by lateral flow in intersected drift excavations, as provided in the FEP description. This distinction is based on the results of *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa, Section 6.3). However, the concern of the FEP is the disruption of the drifts and subsequent damage to the waste package, which is addressed by the TSPA-SR, as described below.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Several Quaternary basaltic volcanoes exist within 20 km of the Yucca Mountain repository, and future igneous activity in the region is of potential concern, although the probability of intersection with the repository is only marginally greater than 1×10^{-8}.

Discussion: Severe perturbation to the integrity of the drifts could hypothetically occur with an igneous event, whether the event was in the form of a sill or a dike. The perturbation could potentially include the damaging of waste packages. 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.

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 or pyroclastic material Regardless of the presence or absence of backfill, the waste packages within the conduit diameter, plus an additional three waste packages on either side of an intrusive dike, are presumed to provide no further protection. Other EBS components in the encompassed area are also presumed to provide no further protection. If backfill is present, damage is presumed to be limited to the area of the conduit plus a distance of three waste packages. If no backfill is present, it is presumed that the remaining waste packages in the intersected drifts are breached by a hole (aperture) of uncertain cross-section area, and that all drip shields and cladding in the intersected dikes are presumed to provide no further protection.

Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

Relation of Elements of Primary FEP Description to Secondary FEPs	
Magma flows into drifts and extends over a portion of the repository site	Sill provides a permeable flow path (1.2.04.03.01) Sill provides a flow barrier (1.2.04.03.02) Volcanism (1.2.04.03.04) Intruding dikes (1.2.04.03.05)
The sill could be limited to the drifts, or a continuous sill could form, bridging between adjacent drifts	Sill intrudes repository openings (1.2.04.03.03) Volcanism (1.2.04.03.04) Intruding dikes (1.2.04.03.05)

Primary FEP: Igneous Intrusion Into the Repository (continued)

References: Supporting documentation for igneous processes are found in multiple documents, including: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m), *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n), *Waste Package Behavior in Magma* CAL-EBS-ME-000002 (CRWMS M&O 1999e), *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z), *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa).

Links to FEPs that examine related but distinct effects and consequences

Tectonic activity—large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Faulting (1.2.02.02.00)
Seismicity associated with igneous activity (1.2.03.03.00)
Basaltic cinder cone erupts through the repository (1.2.04.06.00)
Ashfall (1.2.04.07.00)
Hydrologic response to igneous activity (1.2.10.02.00)

Links to FEPs that examine similar effects and consequences:

Igneous activity (1.2.04.01.00)
Magma interacts with waste (1.2.04.04.00)
Magmatic transport of waste (1.2.04.05.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
IA1: Igneous Activity—Probability
IA2: Igneous Activity—Consequence

Integrated Subissues / Related Subissues:

ENG2: Mechanical Disruption of Barriers / CLST1, CLST2, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3
Direct 1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, SDS1, SDS4,

Primary FEP: Igneous Intrusion Into the Repository (continued)

Primary FEP: Igneous Intrusion Into the Repository
Secondary FEP: Sill provides a permeable flow path

FEP Number: **1.2.04.03.01**	**Originator FEP Description**: A sill develops well-connected cooling fractures. (YMP)	
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion	

Potential Consequences: The elements of the Engineered Barrier System (EBS) and the waste packages could be damaged due to severe perturbation of the drifts, thereby resulting in the release of radionuclides and affecting dose. This FEP was construed to mean that a sill (or dike) intrudes the drift, and cools in the drift and around the damaged waste packages, and forms well-connected fractures.

Discussion: 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. 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.

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 or pyroclastic material. Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

Primary FEP: Igneous Intrusion Into the Repository (continued)

Primary FEP: Igneous Intrusion Into the Repository
Secondary FEP: Sill provides a flow barrier

FEP Number: **1.2.04.03.02**	**Originator FEP Description**: A sill encapsulates waste containers and provides a flow barrier. (YMP)	
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion	

***Potential Consequences**:* The elements of the Engineered Barrier System (EBS) and the waste packages could be damaged due to severe perturbation of the drifts, thereby resulting in the release of radionuclides and affecting dose. This FEP was construed to mean that a sill (or dike) intrudes the drift, and cools in the drift and around the damaged waste packages and forms a flow barrier.

***Discussion**:* 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. 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.

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 or pyroclastic material. Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

Primary FEP: Igneous Intrusion Into the Repository
Secondary FEP: Sill intrudes repository openings

FEP Number: 1.2.04.03.03	**Originator FEP Description**: A dike intrudes under or close to the repository and a sill forms from the dike by intruding into the repository openings. (YMP)	
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion	

***Potential Consequences**:* This FEP was construed to be identical to the Primary FEP Description. Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose, and the elements of the EBS and waste packages could be damaged due to severe perturbation of the drifts, thereby resulting in the release of radionuclides and affecting dose.

***Discussion**:* See Primary FEP Description

Primary FEP: Igneous Intrusion Into the Repository (continued)

Primary FEP: Igneous Intrusion Into the Repository
Secondary FEP: Volcanism

FEP Number: 1.2.04.03.04	Originator FEP Description: A dike intrudes the repository. (Joint SKI/SKB)
Screening Decision: *Included* in the TSPA-SR	Screening Decision Basis: Does not satisfy a screening criterion

Potential Consequences: This FEP was construed to be identical to the Primary FEP Description. Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose, and the elements of the EBS and waste packages could be damaged due to severe perturbation of the drifts, thereby resulting in the release of radionuclides and affecting dose.

Discussion: See Primary FEP Description

Primary FEP: Igneous Intrusion Into the Repository
Secondary FEP: Intruding dikes

FEP Number: 1.2.04.03.05	Originator FEP Description: Volcanic dikes intrude the repository. (Joint SKI/SKB)
Screening Decision: *Included* in the TSPA-SR	Screening Decision Basis: Does not satisfy a screening criterion

Potential Consequences: This FEP was construed to be identical to the Primary FEP Description. Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose, and the elements of the EBS and waste packages could be damaged due to severe perturbation of the drifts, thereby resulting in the release of radionuclides, thereby affecting dose.

Discussion: See Primary FEP Description

Primary FEP: Magma Interacts with Waste

FEP Number: 1.2.04.04.00	Primary 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 (CSNF, DSNF, DHLW).
Primary Assigned to: Disruptive Events FEPs, Waste Package FEPs, Waste Form FEPs	
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion
Number of Secondaries: *6* **Screening Decision**: *All Included* in the TSPA-SR	

Geologic Process: Igneous activity, including both intrusive and eruptive processes.

Potential Consequences: Magma could interact with the elements of the EBS, and waste packages could be damaged (increased degradation or breached) due to severe perturbations in the drifts, thereby resulting in the release of radionuclides and affecting dose.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Several Quaternary basaltic volcanoes exist within 20 km of the Yucca Mountain repository, and future igneous activity in the region is of potential concern, although the probability of intersection with the repository is only marginally greater than 1×10^{-8}.

Discussion: Interactions between the intrusion, the waste, and the waste packages are *Included* in the TSPA-SR, as described in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m, Section 5).

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 or pyroclastic material. Regardless of the presence or absence of backfill, the waste packages within the conduit diameter, plus an additional three waste packages on either side of an intrusive dike, are presumed to provide no further protection. Other EBS components in the encompassed area are also presumed to provide no further protection. If backfill is present, damage is presumed to be limited to the area of the conduit plus a distance of three waste packages. If no backfill is present, it is presumed that the remaining waste packages in the intersected drifts are breached by a hole (aperture) of uncertain cross-section area, and that all drip shields and cladding in the intersected dikes are presumed to provide no further protection.

The TSPA-SR does 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. Attack by magmatic volatiles and mechanical degradation could further damage the packages but would not result in conditions more extreme than presuming that the packages within the conduit diameter (plus three waste packages) provide no further protection. The presumption of damage to remaining packages in the drift for the no-backfill scenario is based on thermal calculations that indicate that deformation of the lid at the end of a waste package at high temperatures (1100 degrees C) and high pressure (7.5 Mpa) may cause failure at the welds between the waste packages and the lid (*Waste Package Behavior in Magma.* CAL-EBS-ME-000002 CRWMS M&O 1999e). Because this type of failure would not remove waste from the package shell, breaching of the packages by an aperture is a reasonable approach.

Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. Dissolution of waste in basaltic melt is not considered explicitly but is conservatively bounded by presuming in the TSPA-SR that waste is exposed directly to groundwater without any protection from the surrounding basalt. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

Primary FEP: Magma Interacts with Waste (continued)

Relation of Elements of Primary Description to Secondary FEPs	
Igneous intrusion intersects waste	Heating of waste container by magma (without contact) (1.2.04.04.04) Fragmentation (1.2.04.04.06)
Waste container failure	Magmatic volatiles attack waste (1.2.04.04.01) Failure of waste container by direct contact w/ magma (1.2.01.04.05)
Dissolution of waste	Dissolution of spent fuel in magma (1.2.04.04.02) Dissolution of other waste in magma (1.2.04.04.03)

References: Supporting documentation for igneous processes are found in multiple documents, including: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m), *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n), *Waste Package Behavior in Magma* CAL-EBS-ME-000002 (CRWMS M&O 1999e), *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z), *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa).

Links to FEPs that examine related but distinct effects and consequences:

Igneous activity (1.2.04.01.00)
Igneous activity causes changes to rock properties (1.2.04.02.00)
Basaltic cinder cone erupts through the repository (1.2.04.06.00)
Ashfall (1.2.04.07.00)
Hydrologic response to igneous activity (1.2.10.02.00)
Cladding unzipping (2.1.02.23.00)
Mechanical failure of cladding (2.1.02.24.00)
Stress corrosion cracking of waste containers and drip shields (2.1.03.02.00)
Mechanical impact on waste container and drip shields (2.1.03.07.00)

Links to FEPs that examine similar effects and consequences:

Igneous intrusion into repository (1.2.04.03.00)
Magmatic transport of waste (1.2.04.05.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
IA1: Igneous Activity—Probability
IA2: Igneous Activity—Consequence

Integrated Subissues / Related Subissues:

ENG2: Mechanical Disruption of Barriers / CLST1, CLST2, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3
Direct1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, SDS1, SDS4
Direct2 Geo: Airborne Transport of Radionuclides

Primary FEP: Magma Interacts with Waste (continued)

Primary FEP: Magma Interacts with Waste
Secondary FEP: Magma volatiles attack waste

FEP Number: 1.2.04.04.01	**Originator FEP Description**: Volatiles [outgassing] from magma (from a dike or sill near to or through the repository) reach containers and waste. These volatiles which are typically aggressive with respect to metals, attack the containers and alter the radionuclide contaminants to soluble forms. (YMP)
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion

Potential Consequences: For this FEP, it is construed that contact with volatile gases has the potential to result in mechanical degradation of the waste package and affect materials inside the waste package. In this way, magma could interact with the elements of the Engineered Barrier System (EBS), and the waste packages could be damaged (increased degradation or breaching), thereby resulting in the release of radionuclides and affecting dose.

Discussion: Interactions between the intrusion, the waste, and the waste packages are *Included* in the TSPA-SR, as described in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m, Section 5).

The TSPA-SR does 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. Attack by magmatic volatiles and mechanical degradation could further damage the packages but would not result in conditions more extreme than presuming that the packages within the conduit diameter (plus three waste packages) provide no further protection. The presumption of damage to remaining packages in the drift for the no-backfill scenario is based on thermal calculations that indicate that deformation of the lid at the end of a waste package at high temperatures (1100 degrees C) and high pressure (7.5 Mpa) may cause failure at the welds between the waste packages and the lid (*Waste Package Behavior in Magma.* CAL-EBS-ME-000002 CRWMS M&O 1999e). Because this type of failure would not remove waste from the package shell, breaching of the packages by an aperture is a reasonable approach.

Primary FEP: Magma Interacts with Waste (continued)

Primary FEP: Magma Interacts with Waste
Secondary FEP: Dissolution of spent fuel in magma

FEP Number: **1.2.04.04.02**	**Originator FEP Description**: Magma intruding into the disposal drifts dissolves spent fuel. (YMP)
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion

***Potential Consequences**:* Magma could interact with the elements of the EBS, and waste packages could be damaged (increased degradation or breaching) due to severe perturbation in the drifts, thereby resulting in the release of radionuclides and affecting dose.

***Discussion**:* 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-SR, as described in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m, Section 5).

Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. Dissolution of waste in basaltic melt is not considered explicitly but is conservatively bounded by presuming in the TSPA-SR that waste is exposed directly to groundwater without any protection from the surrounding basalt. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

Primary FEP: Magma Interacts with Waste (continued)

Primary FEP: Magma Interacts with Waste
Secondary FEP: Dissolution of other waste in magma

FEP Number: 1.2.04.04.03	**Originator FEP Description**: Magma intruding into the disposal drifts dissolves DHLW, DOE spent fuels, or other DOE waste. (YMP)
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion

***Potential Consequences**:* Magma could interact with the elements of the Engineered Barrier System (EBS), and the waste packages could be damaged (increased degradation or breaching) due to severe perturbation in the drifts, thereby resulting in the release of radionuclides and affecting dose.

***Discussion**:* 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-SR, as described in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m, Section 5). All waste types are included in the analysis in the same way that they are *Included* in the TSPA-SR analyses of nominal performance. CNSF is treated as one waste type, and the inventory of all other waste types is aggregated into a second type.

Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. Dissolution of waste in basaltic melt is not considered explicitly but is conservatively bounded by presuming in the TSPA-SR that waste is exposed directly to groundwater without any protection from the surrounding basalt. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

Primary FEP: Magma Interacts with Waste (continued)

Primary FEP: Magma Interacts with Waste
Secondary FEP: Heating of waste container by magma (without contact)

FEP Number: 1.2.04.04.04	**Originator FEP Description**: Waste containers not in direct contact with a dike (or magma flow) are heated as a result of their proximity to the magma. (YMP)
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion

Potential Consequences: For this FEP, it is construed that heating has the potential to result in mechanical degradation or damage of the waste package and affect materials inside the waste package. In this way, magma could interact with the elements of the EBS, and waste packages could be damaged (increased degradation or breaching), thereby resulting in the release of radionuclides and affecting dose.

Discussion: 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-SR, as described in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m, Section 5).

The TSPA-SR does 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. Attack by magmatic volatiles and mechanical degradation could further damage the packages but would not result in conditions more extreme than presuming that the packages within the conduit diameter (plus three waste packages) provide no further protection. The presumption of damage to remaining packages in the drift for the no-backfill scenario is based on thermal calculations that indicate that deformation of the lid at the end of a waste package at high temperatures (1100 degrees C) and high pressure (7.5 Mpa) may cause failure at the welds between the waste packages and the lid (*Waste Package Behavior in Magma*. CAL-EBS-ME-000002 CRWMS M&O 1999e). Because this type of failure would not remove waste from the package shell, breaching of the packages by an aperture is a reasonable approach.

Primary FEP: Magma Interacts with Waste (continued)

Primary FEP: Magma Interacts with Waste
Secondary FEP: Failure of waste container by direct contact with magma

FEP Number: 1.2.04.04.05	**Originator FEP Description**: Waste containers in direct contact with a dike (or magma flow), interact thermally and chemically with the magma. (YMP)
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion

***Potential Consequences**:* Magma could interact with the elements of the EBS, and waste packages could be damaged (increased degradation or breaching) due to severe perturbation of the drifts, thereby resulting in the release of radionuclides and affecting dose.

***Discussion**:* 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-SR, as described in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m, Section 5).

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 or pyroclastic material. Regardless of the presence or absence of backfill, the waste packages within the conduit diameter, plus an additional three waste packages on either side of an intrusive dike, are presumed to provide no further protection. Other EBS components in the encompassed area are also presumed to provide no further protection. If backfill is present, damage is presumed to be limited to the area of the conduit plus a distance of three waste packages. If no backfill is present, it is presumed that the remaining waste packages in the intersected drifts are breached by a hole (aperture) of uncertain cross-section area, and that all drip shields and cladding in the intersected dikes are presumed to provide no further protection.

The TSPA-SR does 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. Attack by magmatic volatiles and mechanical degradation could further damage the packages but would not result in conditions more extreme than presuming that the packages within the conduit diameter (plus three waste packages) provide no further protection. The presumption of damage to remaining packages in the drift for the no-backfill scenario is based on thermal calculations that indicate that deformation of the lid at the end of a waste package at high temperatures (1100 degrees C) and high pressure (7.5 Mpa) may cause failure at the welds between the waste packages and the lid (*Waste Package Behavior in Magma.* CAL-EBS-ME-000002 CRWMS M&O 1999e). Because this type of failure would not remove waste from the package shell, breaching of the packages by an aperture is a reasonable approach.

Primary FEP: Magma Interacts with Waste (continued)

Primary FEP: Magma Interacts with Waste
Secondary FEP: Fragmentation (Note: with subsequent damage to WP)

FEP Number: 1.2.04.04.06	**Originator FEP Description**: Cooling of a magmatic intrusion into the repository, results in the formation of large magma blocks. These fragments subsequently damage waste containers through contact.
Screening Decision: Include	**Screening Decision Basis**: Does not satisfy a screening criterion

Potential Consequences: This FEP is construed to relate to mechanical damage of the waste package by fragments and/or large magma blocks in moving magma. In this way magma could interact with the elements of the EBS, and waste packages could be damaged (increased degradation or breaching) due to severe perturbation of the drifts, thereby resulting in the release of radionuclides and affecting dose.

Discussion: Interactions between the intrusion, the waste, and the waste packages are *Included* in the TSPA-SR, as described in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m, Section 5).

The TSPA-SR does 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. Attack by magmatic volatiles and mechanical degradation could further damage the packages but would not result in conditions more extreme than presuming that the packages within the conduit diameter (plus three waste packages) provide no further protection. The presumption of damage to remaining packages in the drift for the no-backfill scenario is based on thermal calculations that indicate that deformation of the lid at the end of a waste package at high temperatures (1100 degrees C) and high pressure (7.5 Mpa) may cause failure at the welds between the waste packages and the lid (*Waste Package Behavior in Magma*. CAL-EBS-ME-000002 CRWMS M&O 1999e). Because this type of failure would not remove waste from the package shell, breaching of the packages by an aperture is a reasonable approach.

Primary FEP: Magmatic Transport of Waste

FEP Number: 1.2.04.05.00	**Primary 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 surface.
Primary Assigned to: Disruptive Events FEPs, Unsaturated Zone FEPs	
Screening Decision: *Excluded* from the TSPA-SR for transport in liquid magma / *Included* in the TSPA-SR for eruptive transport	**Screening Decision Basis**: Low consequence to dose / Does not satisfy a screening criterion
Number of Secondaries: *3* **Screening Decisions**: All *Excluded* from the TSPA-SR	

Geologic Process: Igneous activity, including both intrusive and eruptive processes.

Potential Consequences: Waste is entrained, dissolved, or volatilized in magma that either remains in the subsurface and is exposed to groundwater or reaches land surface and is then transported.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Several Quaternary basaltic volcanoes exist within 20 km of the Yucca Mountain repository, and future igneous activity in the region is of potential concern, although the probability of intersection with the repository is only marginally greater than 1×10^{-8}. 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 (*Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, Section 6.2 and Table 4).

Discussion:

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 or pyroclastic material. Regardless of the presence or absence of backfill, the waste packages within the conduit diameter, plus an additional three waste packages on either side of an intrusive dike, are presumed to provide no further protection. Other EBS components in the encompassed area are also presumed to provide no further protection. If backfill is present, damage is presumed to be limited to the area of the conduit plus a distance of three waste packages. If no backfill is present, it is presumed that the remaining waste packages in the intersected drifts are breached by a hole (aperture) of uncertain cross-section area, and that all drip shields and cladding in the intersected dikes are presumed to provide no further protection.

Cooling joints would likely form in the basaltic magma during cooling, and some exposure to groundwater would occur. Consequently, no credit is taken for encapsulation of waste and waste-package shells in cooled magma, which could slow or prevent groundwater from reaching the waste. Dissolution of waste in basaltic melt is not considered explicitly but is conservatively bounded by presuming in the TSPA-SR that waste is exposed directly to groundwater without any protection from the surrounding basalt. The subsequent movement of radionuclides in groundwater is modeled directly in the TSPA-SR using existing flow-and-transport models developed for analysis of the nominal performance-assessment scenario. Accordingly, the transport would be dependent on the solubility limits of the exposed waste and the availability of groundwater as modeled for the nominal case. Inputs and parameters are specified in Section 6.2 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m).

Dissolution of waste in basaltic melt is not considered explicitly. However, the TSPA-SR presumption that waste packages damaged by an intrusive igneous event provide no further protection or only partial protection from groundwater entering the drifts effectively bounds the consequence of waste dissolved in the basalt being transported in groundwater. Similarly, volatilized and redeposited radionuclides will not be any more accessible to groundwater transport than the solid waste material exposed in damaged waste packages resulting from an intrusive event, as described above. Transportation of any volatilized radionuclides over the distances for which temperatures will remain high enough will have no additional effect

The critical group is specified by guidance to be located 20 km from the repository. The Quaternary-age volcanic features typically consist of a single main scoria cone surrounded by a small field of *aa* basalts (approximately 1 km extent) (*Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, 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, *Excluded* from the TSPA-SR based on low consequence to dose. However, entrained waste is *Included* in the TSPA-SR for pyroclastic transport into the atmosphere during an eruptive event.

Primary FEP: Magmatic Transport of Waste (continued)

Relation of Elements of the Primary FEP Description to Secondary FEPs:	
Igneous intrusion intersects and entrains waste	Volatile radionuclides plate out in the surrounding rock (1.2.04.05.02) Entrainment of SNF in a flowing dike (1.2.04.05.03)
Waste transported directly to surface	Direct exposure of waste in dike apron (1.2.04.05.01)

References: Supporting documentation for igneous processes is found in multiple documents, including: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m), *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n), *Waste Package Behavior in Magma* CAL-EBS-ME-000002 (CRWMS M&O 1999e), *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z), *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa).

Links to FEPs that examine related but distinct effects and consequences.

Igneous activity (1.2.04.01.00)
Igneous activity causes changes to rock properties (1.2.04.02.00)
Basaltic cinder cone erupts through the repository (1.2.04.06.00)
Ashfall (1.2.04.07.00)
Hydrologic response to igneous activity (1.2.10.02.00)
In-drift sorption (2.1.09.05.00)
Gas transport in waste and EBS (2.1.12.06.00)
Sorption in UZ and SZ (2.2.08.09.00)
Gas transport in geosphere (2.2.11.03.00)
Atmospheric transport of contaminants (3.2.10.00.00)

Links to FEPs that examine similar effects and consequences

Igneous intrusion into repository (1.2.04.03.00)
Magma interacts with waste (1.2.04.04.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
IA1: Igneous Activity—Probability
IA2: Igneous Activity—Consequence

Integrated Subissues / Related Subissues:

ENG2: Mechanical Disruption of Barriers / CLST1, CLST2, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3
Direct1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, SDS1, SDS4
Direct2 Geo: Airborne Transport of Radionuclides

Primary FEP: Magmatic Transport of Waste (continued)

Primary FEP: Magmatic Transport of Waste
Secondary FEP: Direct exposure of waste in dike apron

FEP Number: 1.2.04.05.01	**Originator FEP Description**: An igneous intrusion in the form of a dike occurs through the repository, intersecting waste in transit. Some of the waste (e.g., spent fuel) is dissolved and included in the flowing dike, some of the waste is entrained and carried to the surface in the dike. The dike erupts to form a spatter apron along its course on the surface. The apron contains entrained and dissolved waste. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Waste is entrained, dissolved, or volatilized in magma that either remains in the subsurface and is exposed to groundwater or reaches land surface and is then transported.

***Discussion**:* The critical group is specified by guidance to be located 20 km from the repository. The Quaternary-age volcanic features typically consist of a single main scoria cone surrounded by a small field of *aa* basalts (approximately 1 km extent) (*Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, 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, *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Magmatic Transport of Waste
Secondary FEP: Volatile radionuclides plate out in the surrounding rock

FEP Number: 1.2.04.05.02	**Originator FEP Description**: A volcanic intrusion, interacting with the waste container, heats the contents and vaporizes the volatile radionuclides. These migrate into the nearby rock and plate out. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* This FEP infers that (1) heat is sufficient in the waste package to volatilize waste, and (2) the heat and associated pressure are sufficient to cause the waste package to breach sufficiently for vapor release. Waste is volatilized but remains in the subsurface and is exposed to groundwater.

***Discussion**:* 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 or pyroclastic material. Regardless of the presence or absence of backfill, the waste packages within the conduit diameter, plus an additional three waste packages on either side of an intrusive dike, are presumed to provide no further protection. Other EBS components in the encompassed area are also presumed to provide no further protection. If backfill is present, damage is presumed to be limited to the area of the conduit plus a distance of three waste packages. If no backfill is present, it is presumed that the remaining waste packages in the intersected drifts are breached by an aperture of uncertain cross-section area, and that all drip shields and cladding in the intersected dikes are presumed to provide no further protection.

The TSPA-SR presumption that waste packages damaged by an intrusive igneous event provide no further protection or only partial protection from groundwater entering the drifts effectively bounds the consequence of volatilized waste being available for transport. Volatilized and redeposited radionuclides will not be any more accessible to groundwater transport than the solid waste material exposed in damaged waste packages resulting from an intrusive event, as described above. Transportation of any volatilized radionuclides over the distances for which temperatures will remain high enough will have no additional effect.

Primary FEP: Magmatic Transport of Waste (continued)

Primary FEP: Magmatic Transport of Waste
Secondary FEP: Entrainment of SNF in a flowing dike

FEP Number: 1.2.04.05.03	**Originator FEP Description**: Pieces of spent fuel are entrained in the magma in a flowing dike. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Waste is entrained in magma that either remains in the subsurface and is exposed to groundwater or it reaches land surface and is then transported.

***Discussion**:* The critical group is specified by guidance to be located 20 km from the repository. The Quaternary-age volcanic features typically consist of a single main scoria cone surrounded by a small field of *aa* basalts (approximately 1 km extent) (*Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, 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, *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Basaltic Cinder Cone Erupts through the Repository

FEP Number: 1.2.04.06.00	**Primary FEP Description:** As a result of an igneous intrusion, a cinder cone forms on the surface. The [conduit(s)] supplying the [vent(s)] of the cone [pass(es)] through the repository, interacting with and entraining waste.
Primary Assigned to: Disruptive Events FEPs, Biosphere FEPs	
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis**: Does not satisfy a screening criterion
Number of Secondaries: *2* **Screening Decisions**: *Included* in the TSPA-SR	

Geologic Process: Igneous activity, including both intrusive and eruptive processes.

Potential Consequence: Magma could interact with the elements of the Engineered Barrier System (EBS) and the waste packages could be damaged (increased degradation or breaching) due to severe perturbations in the drifts, thereby, resulting in the release of radionuclides. The radionuclides would then be transported to land surface and into the lower atmosphere during the pyroclastic phase of eruption and transported in the lower atmosphere.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Several Quaternary basaltic volcanoes exist within 20 km of the Yucca Mountain repository, and future igneous activity in the region is of potential concern, although the probability of intersection with the repository is only marginally greater than 1×10^{-8}.

Discussion: Consequences of an igneous intrusion into the repository with an eruptive-phase cinder cone are explicitly *Included* in the TSPA-SR and appropriately weighted by the probability of the occurrence of the event. The TSPA-SR includes explicit modeling of direct releases of contaminated ash during volcanic eruptions, with contaminated ash resulting from conduits intersecting the repository. The modeling of this type of event is described in detail in *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m). This FEP, "Basaltic cinder cone erupts through the repository" (1.2.04.06.00), is *Included* in the TSPA-SR and is addressed through the modeling of the eruptive event.

Relation of Elements of the Primary FEP Description to Secondary FEPs:	
Cinder cone forms, supply to vent passes through the repository	Vent erosion (1.2.04.06.02)
Interacts with and entrains waste	Vent jump(formerly called wander) (1.2.04.06.01)

References: Supporting documentation for igneous processes is found in multiple documents, including: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m), *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n), *Waste Package Behavior in Magma* CAL-EBS-ME-000002 (CRWMS M&O 1999e), *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z), *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa).

Primary FEP: Basaltic Cinder Cone Erupts through the Repository (continued)

Links to FEPs that examine related but distinct effects and consequences:

Tectonic activity — large scale (1.2.01.01.00)
Igneous activity (1.2.04.01.00)
Igneous activity causes changes to rock properties (1.2.04.02.00)
Igneous intrusion into repository (1.2.04.03.00)
Magma interacts with waste (1.2.04.04.00)
Magmatic transport of waste (1.2.04.05.00)

Links to FEPs that examine similar effects and consequences:

Ashfall (1.2.04.07.00)
Atmospheric transport of contaminants (3.2.10.00.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
IA1: Igneous Activity — Probability
IA2: Igneous Activity —Consequence

Integrated Subissues / Related Subissues:

ENG2: Mechanical Disruption of Barriers / CLST1, CLST2, CLST6
Direct1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, SDS1, SDS4
Direct2 Geo: Airborne Transport of Radionuclides
Dose1 Bio: Redistribution of Radionuclides in Soil

Primary FEP: Basaltic Cinder Cone Erupts through the Repository (continued)

Primary FEP: Basaltic Cinder Cone Erupts through the Repository
Secondary FEP: Vent jump (formerly called wander)

FEP Number: 1.2.04.06.01	**Originator FEP Description:** (Identified as "vent wander" by originator) The location of the vent producing a cinder cone is not stable and wanders during the eruption. (YMP).
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis:** Does not satisfy a screening criterion

Potential Consequences: This FEP is concerned with changes in the locations (i.e., wander) of a vent relative to the repository. The FEP addresses concerns that a vent/conduit that forms within the repository footprint increases its area of impact above that of a single event (e.g., resulting in two or more vents). Magma feeding the vents could interact with the elements of the EBS, and waste packages could be damaged (increased degradation or breaching) due to severe perturbations in the drifts, thereby, resulting in the release of radionuclides. The radionuclides would then be transported to land surface and into the lower atmosphere during the pyroclastic phase of eruption.

Discussion: The distributions used for modeling dike characteristics and for the number of eruptive centers within the repository footprint per volcanic event are presented in *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n, Section 6.5.3.2). Of particular note, the conditional distribution for the number of eruptive centers inherently addresses the consequences of Secondary FEP "Vent Jump" (1.2.04.06.01). The conditional distribution of the number of eruptive centers requires the formation of at least one and allows for formation of multiple eruptive centers along a dike or within the repository footprint. Properties of the basaltic eruption are described in *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z) and are based on the observed characteristics of past basaltic eruptions in the Yucca Mountain region and other analogous eruptions.

Primary FEP: Basaltic Cinder Cone Erupts through the Repository
Secondary FEP: Vent erosion

FEP 1.2.04.06.02	**Originator FEP Description:** The vent associated with a cinder cone erodes, increasing in diameter during the eruption. (YMP)
Screening Decision: *Included* in the TSPA-SR	**Screening Decision Basis:** Does not satisfy a screening criterion.

Potential Consequences: Increases in vent diameter and depth could potentially increase the number of waste packages involved during an eruptive event. Magma could interact with the elements of the EBS, and waste packages could be damaged (increased degradation or breaching) due to severe perturbations in the drifts, thereby resulting in the release of radionuclides. The radionuclides would then be transported to land surface and into the lower atmosphere during the pyroclastic phase of eruption.

Discussion: Properties of the basaltic eruption, including the distribution of possible conduit diameters, are described in *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z) 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 range of vent conduit diameters and, thereby, addresses the consequence of the Secondary FEP 1.2.04.06.02 "Vent erosion."

Primary FEP: Ashfall

FEP Number: 1.2.04.07.00	**Primary FEP Description:** Finely-divided waste particles are carried up a volcanic vent and deposited[at land] surface from an ash cloud or pyroclastic flow.
Primary Assigned to: Disruptive Events FEPs, Biosphere FEPs	
Screening Decision: *Included* in the TSPA-SR / *Excluded* from the TSPA-SR for pyroclastic flow.	**Screening Decision Basis**: Does not satisfy a screening criterion / Low consequence to dose
Number of Secondaries: *None* **Screening Decision**: *Not Applicable*	

Geologic Process: Igneous activity, focusing on the eruptive processes

Potential Consequences: Magma could interact with the elements of the EBS, and waste packages could be damaged (increased degradation or breaching) due to severe perturbations in the drifts, thereby resulting in the release of radionuclides. The radionuclides would then be transported to land surface and into the lower atmosphere during the pyroclastic phase of eruption

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Several Quaternary basaltic volcanoes exist within 20 km of the Yucca Mountain repository, and future igneous activity in the region is of potential concern, although the probability of intersection with the repository is only marginally greater than 1×10^{-8}.

Discussion: Inputs and parameters are specified in Section 6.1 of *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m). It is presumed for the TSPA-SR analysis of the eruptive event and subsequent volcanic eruption that waste packages and other components of the EBS that are within the diameter of a conduit provide no further protection from entrainment. It is also presumed that all intrusive events contain an eruptive phase and produce a conduit venting to land surface. Conduits along a dike, including those within the repository footprint, are presumed to be randomly located. Where conduits intersect drifts containing waste, it is presumed that the entire waste content of all intersected waste packages is available to be entrained in the eruption. Waste material is presumed to be fragmented and carried upward in the rising pyroclastic/ash cloud. Because the number of waste packages encountered may vary due to the variability of conduit diameters, and the erupted volume can also vary, 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.

Relation of Elements of the Primary FEP Description to Secondary FEPs: *Not Applicable*

References: Supporting documentation for igneous processes is found in multiple documents, including: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m), *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n), *Waste Package Behavior in Magma* CAL-EBS-ME-000002 (CRWMS M&O 1999e), *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z), *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa).

Primary FEP: Ashfall (continued)

Links to FEPs that examine related but distinct effects and consequences:

Tectonic activity — large scale (1.2.01.01.00)
Seismicity associated with igneous activity (1.2.03.03.00)
Igneous activity (1.2.04.01.00)
Igneous intrusion into repository (1.2.04.03.00)

Links to FEPs that examine similar effects and consequences:

Magma interacts with waste (1.2.04.04.00)
Magmatic transport of waste (1.2.04.05.00)
Atmospheric transport of contaminants (3.2.10.00.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
IA1: Igneous Activity—Probability
IA2: Igneous Activity—Consequence

Integrated Subissues / Related Subissues:

ENG2: Mechanical Disruption of Barriers / CLST1, CLST2, CLST6
Direct1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, SDS1, SDS4
Direct2 Geo: Airborne Transport of Radionuclides
Dose1 Bio: Redistribution of Radionuclides in Soil

Primary FEP: Hydrologic Response to Seismic Activity

FEP Number: 1.2.10.01.00	**Primary 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.
Primary Assigned to: Disruptive Events FEPs, Unsaturated Zone FEPs, Saturated Zone FEPs.	
Screening Decision: *Excluded* from the TSPA-SR *(Preliminary)*	**Screening Decision Basis**: Low consequence to dose
Number of Secondaries: *13* **Screening Decisions***:* All *Excluded* from the TSPA-SR	

Geologic Process: Seismicity

Potential Consequences: Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in connections between stratigraphic units. It could also result in changes in groundwater levels, groundwater temperature, and groundwater chemistry. Cumulatively, these changes have the potential to result in changes in surface- and groundwater flow-and-transport properties. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The peak phase of tectonism took place 12 to 11.6 Ma; the region has since experienced a declining rate of extension. The faults closest to Yucca Mountain are the most important to vibratory ground motion. Ground motion is likely to affect the hydrologic setting through the modification of fracture characteristics. Lithostratigraphic controls affect fracture spacing, type, number of fracture sets, continuity of individual fractures within each lithostratigraphic zone, and also fracture connectivity of the fracture network as a whole (i.e., the fracture connectivity between lithostratigraphic units in the UZ).

Discussion: This FEP includes the effects of seismic activity on UZ and SZ 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). This FEP is more fully addressed in *Features, Events and Processes in UZ Flow and Transport* (CRWMS M&O 2000q, Section 6.7.6).

Regardless of their origin, seismic effects in the UZ would either be transient or result in changes to the hydrologic characteristics of fractures. The matrix- and fracture-parameter values for the hydrogeologic units and the faults are included in the analysis performed in *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000e). The analysis is based on the changing of fracture apertures. Given a change in fracture aperture, other fracture hydrologic properties (permeability, capillary pressure, and porosity) were estimated through the use of theoretical models. Although the analysis particularly addresses the effects of fault displacement, the analysis is mechanistically based only on the change of fracture apertures, regardless of the proximal cause of the change. Therefore, the analysis is potentially applicable to fracturing stemming from thermal, seismic, or tectonic events, as long as the amount of induced changes in fracture aperture are within the range of apertures evaluated in the analysis. This analysis showed that changes in fracture aperture (0.2 times to 10 times the existing fracture aperture) had minimal impact on UZ flow characteristics. The results indicate that radionuclide transport in the UZ of the Yucca Mountain region is relatively insensitive to large variations in fracture aperture. Because radionuclide transport is not affected, dose is not affected. Therefore, seismic effects on the UZ are *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity (continued)

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 m within an hour of a simulated seismic event. The simulated system returns to steady-state conditions within six 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."

Because seismic effects have been shown to have a minimal effect on groundwater flow, there is no mechanism for seismic effects to significantly affect the dose. Consequently, this FEP is *Excluded* based on low consequence to dose.

Relation of Elements of Primary FEP Description to Secondary FEPs:	
New or enhanced flow pathways/ connections between stratigraphic units	New faulting breaches flow barrier controlling large hydraulic gradient to the north (1.2.10.01.03) Head driven flow up from carbonates (1.2.10.01.05) Fault pathway through the altered Topopah Springs basal vitrophyre (1.2.10.01.07) Fault movement connects tuff and carbonate aquifers (1.2.10.01.08) Fault establishes pathway through the UZ (1.2.10.01.09) Fault establishes pathway through the SZ (1.2.10.01.10)
Change of stress	Normal faulting produces a trap for laterally moving moisture in the Tiva Canyon Unit (1.2.10.01.04)
Change to surface- and groundwater flow directions, groundwater levels, groundwater chemistry, and temperature	Fault movement pumps fluid from SZ to UZ (seismic pumping) (1.2.10.01.01) Fault creep causes short term fluctuation of the water table (1.2.10.01.02) Seismically-induced water table changes (1.2.10.01.06) Fluid supplied by fault migrates down the drift (1.2.10.01.11) Fault intersects and drains condensate zone (1.2.10.01.12) Flow barrier south of the site blocks flow, causing water table to rise (1.2.10.01.013)

References: Supporting documentation for the evaluation of the impact of changes of fracture apertures is provided in CRWMS M&O (2000e). See also *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000q) and *Features, Events, and Processes in SZ Flow and Transport* ANL-NBS-MD-000002 (CRWMS M&O 2000r).

Links to FEPs that examine related but distinct effects and consequences:

Tectonic activity — large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Faulting (1.2.02.02.00)
Seismicity associated with igneous activity (1.2.03.03.00)
Igneous activity causes changes to rock properties (1.2.04.02.00)
Hydrologic response to igneous activity (1.2.10.02.00)

Links to FEPs that examine similar effects and consequences:

Water-table rise (1.3.07.02.00)
Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock (2.2.06.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults (2.2.06.02.00)
Changes in stress (due to seismic or tectonic effects) alter perched water zones (2.2.06.03.00)

Primary FEP: Hydrologic Response to Seismic Activity (continued)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS1: Faulting
SDS2: Seismicity
SDS3: Fractures

Integrated Subissues / Related Subissues:

ENG3: Quantity and Chemistry of Water Contacting the Waste Package and Waste Form / ENFE1, ENFE2, CLST1, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS2, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS1, SDS2, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS1, SDS2, SDS3

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Fault movement pumps fluid from SZ to UZ (seismic pumping)

FEP Number: 1.2.10.01.01	**Originator FEP Description**: Fault movement relieves stress (increased fluid pressure in pores and fractures) in the saturated zone by driving water up fractures in the unsaturated zone, thus raising the water table. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties. Of particular concern in the FEP description is the rise of the water table. This could either change hydraulic heads (and thus change flow conditions) or, if a large enough rise were to occur, cause flow into the repository. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides

***Discussion**:* See Screening Arguments in *Features, Events, and Processes in UZ Flow and Transport* (CRWMS M&O (2000q). 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 m within an hour of a simulated seismic event. The simulated system returns to steady-state conditions within six months. Because the effect is insufficient to raise the water table to the level of the repository, and because the effect is transient, the impact on groundwater-flow conditions is insignificant. Because groundwater-flow conditions are not significantly changed, dose is not significantly changed, and the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity (continued)

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Fault creep causes short term fluctuation of the water table

FEP Number: 1.2.10.01.02	**Originator FEP Description**: Fault creep includes minor restructuring of the in situ strain-energy field. This change causes short-term stress-induced fluctuations in the level of the water table. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Seismic activity has the potential to result in movement along faults (creep) or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties. Of particular concern in the FEP description is the rise of the water table. This could either change hydraulic heads (and thus change flow conditions) or, if a large enough rise were to occur, cause flow into the repository. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides

Discussion: See Screening Arguments in *Features, Event, and Processes in UZ Flow and Transport* (CRWMS M&O (2000q)). 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 m within an hour of a simulated seismic event. The simulated system returns to steady-state conditions within six months. Because the effect is insufficient to raise the water table to the level of the repository, and because the effect is transient, the impact on groundwater-flow conditions is insignificant. Because groundwater-flow conditions are not significantly changed, dose is not significantly changed, and the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: New faulting breaches flow barrier controlling large hydraulic gradient to the north

FEP Number: 1.2.10.01.03	**Originator FEP Description**: Fracturing along a new fault creates a permeable pathway through the flow barrier assumed to control the large hydraulic gradient and the water table rises to the top of the Calico Hills unit. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Seismic activity could create new faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties. This FEP is particularly focused on the large hydraulic gradient north of the repository site.

Discussion: See Screening Arguments in *Features, Events, and Processes in UZ Flow and Transport* (CRWMS M&O (2000q). This FEP is predicated on the presumptions that: (1) a new fault is created, (2) fracturing associated with the fault is of sufficient width or magnitude to breach the flow barrier, and (3) the flow barrier is primarily a permeability-controlling feature. The possibility of new faulting within the repository block is addressed in the PSHA (USGS 1998) through consideration of the potential for displacement of intact rock and was found to have a low possibility of even minimal displacement. Consequently, creation of a new fault is a low-probability event. Additionally, as described for the Primary FEP "Fracturing" (1.2.02.01.00), the width of the zone of influence on fracture frequency in the immediate vicinity of a fault is, in general, quite narrow, ranging from less than 1 m to about 7 m from the fault and correlates, in a general way, with the amount of cumulative fault offset. The width of the zone of influence around a fault does not appear to be related to depth. The amount of deformation associated with faults appears, in part, to be dependent upon which lithologic unit that is involved in the faulting. Lithostratigraphic controls affect fracture spacing, type, number of fracture sets, continuity of individual fractures within each lithostratigraphic zone, and the fracture connectivity of the network as a whole. Consequently, the presumption of fracturing being sufficient to result in a permeable pathway, on a qualitative basis, seems unlikely. Lastly, site data suggest that the large hydraulic gradient is not a result of residual stress (i.e., in an area prone to new faulting) and is more reasonably explained by differences in lithology, alteration history, and structural deformation. Consequently, fracturing or faulting would result in minimal changes to the hydraulic gradient. Because flow conditions would not be significantly altered, the dose would not be significantly affected, and the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity (continued)

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Normal faulting produces a trap for laterally moving moisture in the Tiva Canyon unit

FEP Number: 1.2.10.01.04	**Originator FEP Description**: Normal faulting produces a trap intercepting laterally moving moisture in the Tiva Canyon unit and increases flux in the Topopah Spring units. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

***Discussion**:* See Screening Arguments in *Features, Events, and Processes in UZ Flow and Transport* (CRWMS M&O (2000q)). The probability of new faulting in intact rock is below the screening criteria, and movement on existing faults is of small magnitude (less than 1 m) as indicated in the PSHA (USGS 1998). Also, the effect of changes to fracture apertures (10 times to 0.2 time the existing fracture apertures) both at the mountain scale and in fault zones has been analyzed and shown to have minimal effect on radionuclide transport. Therefore, the mechanism for forming the trap does not appear to have the potential to result in significant changes to the groundwater-flow condition. Because no significant change to flow conditions occurs, there is no significant change in dose, and the FEP is *Excluded* based on low consequence to dose.

Primary FEP: **Hydrologic Response to Seismic Activity**
Secondary FEP: **Head driven flow up from carbonates**

FEP Number: 1.2.10.01.05	**Originator FEP Description**: A fault connection of the EBS, UZ, and SZ allows water flow up the fault from the carbonates to the EBS. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties, including water-table rise. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides

***Discussion**:* See Screening Arguments in CRWMS M&O (2000q). This FEP presumes that heads in the carbonate aquifer are sufficient to rise up a conductive fault plane to the repository level. This would require hydraulic heads in the carbonate aquifer to be in excess of 1000 m. There are no indications that heads in the carbonate aquifer are of this magnitude. Because the physical conditions for this FEP do not occur, this FEP does not have the potential to create any significant change in groundwater-flow characteristics. Because groundwater-flow characteristics are not significantly affected, there is no significant potential to affect dose. Therefore, the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity (continued)

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Seismically-induced water table changes

FEP Number: 1.2.10.01.06	**Originator FEP Description**: As a result of distant earthquakes, the local water-table-elevation changes. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties, including water-table rise. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: See Screening Arguments in CRWMS M&O (2000q). 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 m within an hour of a simulated seismic event. The simulated system returns to steady-state conditions within six months. Because the effect is insufficient to cause the water table to rise to the level of the repository, and because the effect is transient, the impact on groundwater-flow conditions is insignificant. Because groundwater-flow conditions are not significantly changed, dose is not significantly changed, and the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Fault pathway through the altered Topopah Springs basal vitrophyre

FEP Number: 1.2.10.01.07	**Originator FEP Description**: Movement along an old fault or creation of a new fault generates a pathway [through] the altered Topopah Spring basal vitrophyre. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides

Discussion: See Screening Arguments in CRWMS M&O (2000q). The probability of new faulting in intact rock is below the screening criteria probability, and movement on existing faults is of small magnitude (less than 1 m), as indicated in the PSHA (USGS 1998). Also, the effect of changes to fracture apertures (0.2 times to 10 times the existing fracture apertures) both at the mountain scale and in fault zones has been analyzed and shown to have minimal effect on radionuclide flow and transport (*Fault Displacement Effects on UZ Transport* CRWMS M&O 2000e). Therefore, the mechanism for forming the pathway does not appear to result in significant changes to the flow condition. Because no significant change to flow conditions occurs, there is no significant change in dose, and the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity (continued)

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Fault movement connects tuff and carbonate aquifers

FEP Number: 1.2.10.01.08	**Originator FEP Description**: A new fault or movement on an old fault establishes a connection between the tuff aquifers and the carbonate aquifers. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is similar to the above Secondary FEP "Head driven flow up from carbonates " (1.2.10.01.07). Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties, including water-table rise. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides

Discussion: See Screening Arguments in *Features, Events, and Processes in UZ Flow and Transport* (CRWMS M&O (2000q).

The probability of new faulting in intact rock is below the screening criteria, and movement on existing faults is of small magnitude (less than 1 m), as indicated in the PSHA (USGS 1998). Also, the effect of changes to fracture apertures (0.2 times to 10 times the existing fracture apertures) both at the mountain scale and in fault zones has been analyzed and shown to have minimal effect on radionuclide transport (*Fault Displacement Effects on Transport in the Unsaturated Zone* CRWMS M&O 2000e). This FEP also presumes, in part, that heads in the carbonate aquifer are sufficient to rise up a conductive fault plane to the repository level. This would require hydraulic heads in the carbonate aquifer to be in excess of 1000 m. There are no indications that heads in the carbonate aquifer are of this magnitude.

Because the physical conditions for this FEP do not occur, this FEP does not have the potential to create any significant change in groundwater-flow characteristics. Because groundwater-flow characteristics are not significantly affected, there is no significant potential to affect dose. Therefore, the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Faults establishes pathway through UZ

FEP Number: 1.2.10.01.09	**Originator FEP Description**: Movement along an old fault or creation of a new fault generates a pathway through the UZ. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is similar to the above Secondary FEP "Fault movement connects tuff and carbonate aquifers" (1.2.10.01.08). Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties, including water-table rise. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: See Screening Arguments in *Features, Events, and Processes in UZ Flow and Transport* (CRWMS M&O (2000q). See the preceding discussion for "Fault movement connects tuff and carbonate aquifers" (1.2.10.01.08).

Primary FEP: Hydrologic Response to Seismic Activity (continued)

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Fault establishes pathway through the SZ

FEP Number: 1.2.10.01.10	**Originator FEP Description**: Movement along an old fault or creation of a new fault generates a flow path in the SZ. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is similar to the above Secondary FEP "Fault movement connects tuff and carbonate aquifers" (1.2.10.01.08). Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties, including water-table rise. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: See Screening Arguments in *Features, Events, and Processes in UZ Flow and Transport* (CRWMS M&O (2000q). See the preceding discussion for "Fault movement connects tuff and carbonate aquifers" (1.2.10.01.08).

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Fluid supplied by a fault migrates down the drift

FEP Number: 1.2.10.01.11	**Originator FEP Description**: A pathway established by fault movement through the repository brings fluid to the drift; fluid which migrates down the drift to transport contaminants down other pathways in the UZ. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: See Screening Arguments in CRWMS M&O (2000q). The probability of new faulting in intact rock is below the screening criteria, and movement on existing faults is of small magnitude (less than 1 m), as indicated in the PSHA (USGS 1998). Also, the effect of changes to fracture apertures (0.2 times to 10 times the existing fracture apertures) both at the mountain scale and in fault zones has been analyzed and shown to be minimal on radionuclide flow and transport (*Fault Displacement Effects on Transport in the Unsaturated Zone* CRWMS M&O 2000e). Therefore, the mechanism for forming the path does not appear to result in significant changes to the flow condition. Because no significant change to flow conditions occur, there is no significant change in dose, and the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity (continued)

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Fault intersects and drains condensate zone

FEP Number: 1.2.10.01.12	Originator FEP Description: Movement on a fault (new or old) intersects a condensate zone above the drifts and the fault drains the condensate into one or more drifts. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: See Screening Arguments in CRWMS M&O (2000q). The probability of new faulting in intact rock is below the screening criteria, and movement on existing faults is of small magnitude (less than 1 m) as indicated in the PSHA (USGS 1998). Also, the effect of changes to fracture apertures (0.2 times to 10 times the existing fracture apertures) both at the mountain scale and in fault zones has been analyzed and shown to be minimal on radionuclide flow and transport (*Fault Displacement Effects on Transport in the Unsaturated Zone* CRWMS M&O 2000e). Therefore, the mechanism for forming the path does not appear to result in significant change to the flow condition. Because no significant change to the flow condition occurs, there is no significant change in dose, and the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Seismic Activity
Secondary FEP: Flow barrier south of the site blocks flow, causing water table to rise

FEP Number: 1.2.10.01.13	Originator FEP Description: As in YSCP15, fault-caused fracturing breaches the flow barrier north of the repository block. Flow is blocked by another barrier, not apparent from the current head distribution, and the resulting rise in water table floods the repository. Water passing through the repository discharges through springs in Forty mile Wash. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Seismic activity has the potential to result in movement along faults or changes in rock stresses, resulting in changes in groundwater flow-and-transport properties. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: See Screening Arguments in CRWMS M&O (2000q). See also the preceding discussion for the Secondary FEP "New faulting breaches flow barrier controlling large hydraulic gradient to the north" (1.2.10.01.03). This FEP is predicated on the presumption that the flow barrier north of the repository is somehow breached. As previously discussed for the referenced Secondary FEP, the proposed phenomenon for this event has been *Excluded* based on low consequence to dose. The FEP description in this case also presupposes a secondary barrier south of the repository. Existing data does not support the presumption of the existence of a second barrier to the south. If such a barrier were to exist and be significant to dose at a distance of 20 km from the repository, it is also reasonable to presume that its presence would be detectable from existing head data. The FEP also presumes that the barrier would be sufficient to cause a 300-m rise in the water table at the repository location. Because the mechanisms for affecting groundwater flow and flooding the repository (see description above) are not present, there is no mechanism for hydrologic response to seismic activity to significantly affect dose. Therefore, the FEP is *Excluded* based on low consequence to dose.

Primary FEP: Hydrologic Response to Igneous Activity

FEP Number: 1.2.10.02.00	**Primary 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.
Primary Assigned to: Disruptive Events FEPs, Saturated Zone FEPs, Unsaturated Zone FEPs	
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose
Number of Secondaries: *2* **Screening Decisions**: Both *Excluded from the TSPS-SR*	

Geologic Process: Igneous activity, focusing on intrusive processes.

Potential Consequence: 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. Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose. Additionally, the elements of the EBS and waste packages could be damaged due to increased flow through the drifts, leading to increased degradation rates and premature failures, thereby resulting in the release of radionuclides, and consequently affecting dose.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. Several Quaternary basaltic volcanoes exist within 20 km of the Yucca Mountain repository, and future igneous activity in the region is of potential concern, although the probability of intersection with the repository is only marginally greater than 1×10^{-8}. Groundwater flow in the UZ and SZ are greatly influenced by fractures. Lithostratigraphic controls affect fracture spacing, type, number of fracture sets, continuity of individual fractures within each lithostratigraphic zone, and also the fracture connectivity of the network as a whole

Discussion: The effects of igneous activity on the UZ are discussed more fully in *Features, Events and Processes in UZ Flow and Transport* (CRWMS M&O 2000q, Sections 6.7.7). Formation of perched water in the UZ above the repository and subsequent focused flow are addressed in the TSPA-SR indirectly through the seepage-model abstraction. Drainage of perched-water zones below the repository was *Excluded* based on low consequence to dose, because the minimal volume of water involved would not affect dose from the saturated zone.

The margins of dikes are associated with near-vertical jointing (Valentine et al. 1998, p. 5-32), and future dikes are likely to be oriented parallel to the direction of existing anisotropic transmissivity in the SZ in the vicinity of Yucca Mountain (CRWMS M&O 2000aa), consistent with existing fault and fracture orientation (Ferrill, Winterle et al. 1999, p. 1). Because of the fractured nature of intrusive dikes and the parallel orientation of dikes with the existing orientation of the anisotropic maximum horizontal permeability in the SZ, 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 1998c, Section 10.5.3) suggests that intrusion of a dike would have negligible impact on repository performance due to changes in flow in the SZ. Because (1) formation of a dike in the repository is a relatively infrequent occurrence, (2) dikes are fractured, and (3) dikes would most likely form parallel to the existing groundwater-flow directions, there is no apparent mechanism for dikes to significantly change the groundwater flow. Consequently, there is no mechanism for significantly changing the dose.

Based on natural-analogue and preliminary modeling studies, the zones of alteration and hydrothermal effects around dikes are extremely limited (Valentine et al. 1998, pp. 5-41, 5-46, 5-57, and 5-74). This suggests that little destruction of sorptive minerals or hydrothermal effects is expected. Given the limited area of alteration around the intrusion, the effect of alteration on radionuclide transport characteristics of the host rock would be negligible, and the consequence to dose would also be negligible The development of hydrothermal systems from igneous activity is also expected to be minimal and not significantly effect groundwater-flow patterns. Because groundwater flow over a large area (respective to the repository) is not affected, the dose is not expected to be affected. This FEP is, therefore, *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Hydrologic Response to Igneous Activity (continued)

Relation of Elements of the Primary FEP Description to Secondary FEPs:	
Groundwater-flow directions, water level, water chemistry	Interaction of water table with magma (1.2.10.02.01) Interaction of unsaturated zone pore water with magma (1.2.10.02.02)
Rock properties and flow pathways	(No Secondary FEPs relate to this element)
Temperature and thermal effects	Interaction of water table with magma (1.2.10.02.01) Interaction of unsaturated zone pore water with magma (1.2.10.02.02)

References: Supporting documentation for igneous processes are found in multiple documents, including: *Igneous Consequence Modeling for the TSPA-SR* ANL-WIS-MD-000017 (CRWMS M&O 2000m), *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* ANL-MGR-GS-000001 (CRWMS M&O 2000n), *Waste Package Behavior in Magma* CAL-EBS-ME-000002 (CRWMS M&O 1999e), *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000z), *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa). See also *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000q) and *Features, Events, and Processes in SZ Flow and Transport* ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Links to FEPs that examine related but distinct effects and consequences:

Tectonic activity — large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Faulting (1.2.02.02.00)
Seismicity associated with igneous activity (1.2.03.03.00)
Hydrologic response to seismic activity (1.2.10.01.00)

Links to FEPs that examine similar effects and consequences:

Igneous activity causes changes to rock properties (1.2.04.02.00)
Water-table rise (1.3.07.02.00)
Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock (2.2.06.01.00)
Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults (2.2.06.02.00)
Changes in stress (due to seismic or tectonic effects) alter perched water zones (2.2.06.03.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
IA2: Igneous Activity—Consequence
SDS3: Fractures

Integrated Subissues / Related Subissues:

ENG3: Quantity and Chemistry of Water Contacting the Waste Package and Waste Form / ENFE1, ENFE2, CLST1, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3

Primary FEP: Hydrologic Response to Igneous Activity (continued)

Primary FEP: Hydrologic Response to Igneous Activity
Secondary FEP: Interaction of water table with magma

FEP Number: 1.2.10.02.01	**Originator FEP Description**: (No Description)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Listed issues from the FEP database text include heating and steam explosion. Based on the reference to interaction with the water table, this FEP is construed to apply to effects in the SZ only. Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose.

***Discussion**:* The listed concern is the possibility that a large steam explosion could occur, such that a large phreatic or a phreatomagmatic crater (maar) forms. 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 and, as the steam violently expands, to allow disruption of the surrounding rock. These mechanisms were considered by Crowe et al. (1986, p. 58-59). Although rising magma at Yucca Mountain would contact water in the saturated zone, Crowe et al. (1986) 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."

Primary FEP: Hydrologic Response to Igneous Activity
Secondary FEP: Interaction of unsaturated zone pore water with magma

FEP Number: 1.2.10.02.02	**Originator FEP Description**: Issues: heating, steam explosion
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Based on the reference to interaction with UZ pore water, this FEP is construed to apply to heating effects in the UZ only. The most probable effect would be hydrothermal alteration of minerals. Igneous activity could potentially alter the hydrologic characteristics of the site, thereby affecting flow-and-transport characteristics and affecting dose.

***Discussion**:* Based on natural-analogue and preliminary modeling studies, the zones of alteration and hydrothermal effects around dikes are extremely limited (Valentine et al. 1998, pp. 5-41, 5-46, 5-57, and 5-74). This suggests that little destruction of sorptive minerals or hydrothermal effects are expected. Given the limited area of alteration around the intrusion, the effect of alteration on radionuclide transport characteristics of the host rock would be negligible. The development of hydrothermal systems from igneous activity is also expected to be minimal and not significantly affect groundwater-flow patterns. Because groundwater flow over a large area (respective to the repository) is not affected, the dose is not expected to be affected, and interaction of the UZ pore water with magma is, therefore, *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Rockfall (Large Block)

FEP Number: 2.1.07.01.00	**Primary FEP Description:** Rockfalls occur large enough to mechanically tear or rupture waste packages
Primary Assigned to: Disruptive Events FEPs, Thermal Hydrology and Coupled Processes FEPs, Waste Form FEPs, Waste Package FEPs	
Screening Decision: *Excluded* from the TSPA-SR *(Preliminary)*	**Screening Decision Basis**: Low consequence to dose
Number of Secondaries: *4* **Screening Decisions***:* All *Excluded* from the TSPA-SR	

Geologic Process: Tectonism / Seismicity

Potential Consequences: With time and changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. Large blocks (e.g., key blocks) may form at the intersection of three or more planes of structural discontinuity. A triggering event (vibratory ground motion) may have the potential to cause movement of the key block, and cause it to fall onto the drip shield and/or waste packages. This may be of particular concern for the no-backfill design. The drip shield and/or waste packages may be ruptured or torn and release radionuclides for transport. Water may flow through tears or ruptures to transport the radionuclides from the repository.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. Stress regimes are as described by Savage et al. 1999.

Discussion: 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 (CRWMS M&O 2000i) for the design that included backfill (CRWMS M&O 1999a, pp. 4-16 and 4-17) and also incorporated the results of a supporting calculation (CRWMS M&O 2000j) for a no-backfill design with reoriented drifts (CRWMS M&O 2000b). The current design (CRWMS M&O 2000b) includes a drip shield and drifts oriented along azimuth 252.

The impact of rockfall on the drip shield is discussed in *Rock Fall on Drip Shield,* CAL-EDS-ME-000001 (CRWMS M&O 2000t). The calculation indicates that no cracks develop (i.e., no breaching occurs) in the drip shield due to the dynamic impact of a rock on the drip shield for an effective rock mass of 10 MT over a 3-m length of drip shield, or up to a key-block size of 52 MT. The maximum key-block size expected is 37 MT. This calculation presumes that the rock block does not fail at impact and also based on the material characteristics provided in Section 5 of the calculation. The presence of the drip shield, therefore, precludes rockfall as a credible scenario contributing to direct waste-package failure (i.e., breaching). Stress-corrosion cracking in the drip shield may, however, result from residual stresses depending on the size of the rock.

The occurrence of large key-block rockfall is relatively infrequent, and the largest estimated key block is smaller than that used in the analysis for drip shield damage. The analysis (CRWMS M&O 2000t) indicates that no breaching of the drip shield will occur due to rockfall, even with the larger block sizes associated with seismic and thermal loading. Even if the drip shield were to be ruptured, the force of the impact would be absorbed by the drip shield and would not be transferred completely to the waste package. The waste package itself is also being designed to withstand rockfall events.

Because there is no mechanism present from rockfall to rupture the drip shield, there is no mechanism for rockfall to increase radionuclide release. If no radionuclide release occurs due to rockfall, there is no significant change to dose. Consequently, the FEP is *Excluded* from the TSPA-SR based on low consequence to dose. The secondary FEPs, which include the impact of rockbursts on waste packages (see Attachment II), are also *Excluded* from the TSPA-SR.

Primary FEP: Rockfall (Large Block)(continued)

Relation of Elements of Primary FEP Description to Secondary FEPs	
Rockfall (large)	Cave ins (2.1.07.01.02) Cave ins (in waste and EBS) (2.1.07.01.03) Roof falls (2.1.07.01.04)
Mechanical tearing or rupture of waste packages	Rockbursts in container holes (2.1.07.01.01)

References: The supporting documentation pertaining to seismicity are found in the PSHA (USGS 1998) and in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* ANL-CRW-GS-000003 (CRWMS M&O 2000k). 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 (CRWMS M&O 2000i) for the design including backfill (*License Application Design Selection Report* B00000000-01717-1705-00011 CRWMS M&O 1999a, pp. 4-16 and 4-17) and includes the results of a supporting calculation (*Supporting Calculation for Drift Degradation* CAL-EBS-MD-000010 CRWMS M&O 2000j) for a no-backfill design with drip shield, with drifts reoriented to azimuth 75. The impact of rockfall on the drip shield is discussed in *Rock Fall on Drip Shield,* CAL-EDS-ME-000001 (CRWMS M&O 2000t).

Links to FEPs that examine related but distinct consequences and events

Tectonic activity—large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Seismic activity (1.2.03.01.00)
Rock properties of host rock and other units (2.2.03.02.00)

Links to FEPs that examine similar consequences and events

Mechanical failure of cladding (2.1.02.24.00)
Mechanical impact on waste container and drip shield (2.1.03.07.00)
Effects and degradation of drip shield (2.1.06.06.00)
Mechanical degradation or collapse of drift (2.1.07.02.00)
Thermally induced stress changes in waste and EBS (2.1.11.07.00)

Links to IRSRs;

Directly Related KTI Subissues:

TSPAI 1: Features, Events and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME2: Seismic Design
RDTME3: Thermal Mechanical Effects

Integrated Subissues / Related Subissues:

ENG1: Degradation of Barriers / TEF2, ENFE2, CLST1, CLST2, CLST6
ENG2: Mechanical Disruption of Barriers / CLST1, CLST 2, CLST6, SDS2, SDS3, SDS4, RDTME2
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS2, SDS3

Primary FEP: Rockfall (Large Block)(continued)

Primary FEP: Rockfall (Large Block)
Secondary FEP: Rockbursts in container holes

FEP Number: 2.1.07.01.01	**Originator FEP Description**: Rock bursts propel rocks into waste packages and puncture the canisters. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: As noted in the YMP FEP Database, this FEP specifically applies to a vertical design option utilizing in-floor vertical borehole emplacement with a 1-cm air gap, which is no longer considered. The current design is horizontal, in-drift emplacement of very large container. The mechanism of failure in the FEP is the sudden release of energy, propelling a rock out of the drift wall and into the waste package. This FEP has been construed to apply to rockbursts from the roof or drift wall on to a horizontally-oriented drip shield or waste package. If the rockburst were to occur, it has the potential to impact the drip shield and/or waste packages by breaching, thereby leading to the release of radionuclides for transport. Water may flow through the tear or rupture to transport the radionuclides from the repository.

Discussion: With the presence of the drip shield, the projectile mechanism of failure of the waste package is no longer a credible event because the drip shield will absorb the impact of the projectile. A corollary with rockfall events can be made through consideration of the energy involved. Small projectiles with low mass but traveling at high velocities may impact with the same force as large masses (i.e., key blocks) traveling at lower velocities. The impact of rockfall on the drip shield is discussed in *Rock Fall on Drip Shield,* CAL-EDS-ME-000001 (CRWMS M&O 2000t). The calculation indicates that no cracks develop (i.e., no breaching occurs) in the drip shield due to the dynamic impact of a rock on the drip shield for an effective rock mass of 10 MT over a 3-m length of drip shield, or up to a key-block size of 52 MT. The presence of the drip shield, therefore, precludes rockfall as a credible scenario contributing to direct waste-package failure (i.e., breaching) and qualitatively suggests that rockbursts are also not of concern.

Additionally, the design criteria for the uncanistered, spent-nuclear-fuel waste packages indicate that the packages must be able to withstand small projectile impacts, a 6-MT rockfall event, a vertical drop of 2 m in the vertical position, and a drop of 2.4 m in the horizontal position. (CRWMS M&O 2000v).

Because of the design of the drip shield and the waste packages, there does not appear to be a credible mechanism from rockbursts for breaching the drip shield or the waste packages. Thus, no mechanism from rockbursts is present for the release of radionuclides, and consequently, dose is not significantly changed. Therefore, this FEP is *Excluded* based on low consequence to dose.

Primary FEP: Rockfall (Large Block)(continued)

Primary FEP: **Rockfall (Large Block)**
Secondary FEP: Cave ins

FEP Number: 2.1.07.01.02	**Originator FEP Description**: Cave-ins and stress induced fracturing of rock may occur, changing the characteristics of buffer and backfill. (AECL)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP presumes the use of buffer and backfill and it is not specific regarding the characteristics that could be affected. Because cave-ins are mentioned in the description, this FEP is construed to apply to the backfill's tendency to mitigate rockfall impact to the drip shield. With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. Large blocks (e.g., key blocks) may form at the intersection of three or more planes of structural discontinuity. A triggering event may cause movement or fall of the key block onto the drip shield and/or waste packages. The drip shield and/or waste packages may be ruptured or torn and may release radionuclides for transport. Water may flow through the tear or rupture to transport the radionuclides from the repository.

Discussion: An analysis of the possible formation of key blocks within the repository horizon has been provided by CRWMS M&O (2000i) for the design that included backfill (CRWMS M&O 1999a, pp. 4-16 and 4-17),and incorporates the results of a calculation (CRWMS M&O 2000j) for a no-backfill design with reoriented drifts (CRWMS M&O 2000b). The current design (CRWMS M&O 2000b) includes a drip shield and drifts oriented along azimuth 252.

The analysis in CRWMS M&O (2000j) provides the number and size distribution of key blocks that are likely to occur. Rockfall of any type is an infrequent event, with the maximum density of rockfalls of 32 per km of drift in a 10,000-year period, and with 75 percent of the key blocks being of 0.24 m^3 or less (*Rock Fall on Drip Shield,* CAL-EDS-ME-000001 CRWMS M&O 2000j, Tables 12 and 15). In some instances the key block density is as little as 2 per km. Consequently, buffer or stability issues and/or thermal build-up are not credible events. Additionally, the projected rockfall sizes are inadequate to breach the drip shield.

Because (1) there is no mechanism from cave-ins present to significantly affect the backfill characteristics, (2) rockfall is of insufficient size to rupture the drip shield, and (3) the most current design is evaluated as a no-backfill design, there is no apparent mechanism present from rockfall that leads to a radionuclide release. If no radionuclide release occurs due to rockfall, there is no significant change to dose. Consequently, the FEP is *Excluded* from the TSPA-SR based on low consequence to dose. The secondary FEPs, which includes the impact of rockbursts on waste packages (see Attachment II), are also *Excluded* from the TSPA-SR.

Primary FEP: Rockfall (Large Block)(continued)

Primary FEP: Rockfall (Large Block)
Secondary FEP: Cave in (in waste and EBS)

FEP Number: 2.1.07.01.03	**Originator FEP Description:** If the mechanical supporting properties of the bentonite buffer or tunnel backfill decrease, the mechanical stability of the rock adjacent to deposition holes and tunnels is affected. Loss of mechanical stability may cause movements of rock blocks, and in extreme cases collapse of a deposition hole or a tunnel section. (SKI)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* This FEP description is based on a non-Yucca Mountain design as suggested by the use of the term "deposition hole." However, it also specifies the effect on tunnels, which correlate to the use of drifts in the Yucca Mountain repository design. Consequently, this FEP is construed to apply to either backfill or no-backfill design for drifts. With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. Large blocks (e.g., key blocks) may form at the intersection of three or more planes of structural discontinuity. A triggering event may cause movement or fall of the key block onto the drip shield and/or waste packages. The drip shield and/or waste packages may be ruptured or torn and release radionuclides for transport. Water may flow through the tear or rupture to transport the radionuclides from the repository.

***Discussion**:* The drip shield analysis was done to address both backfill and no-backfill design. The analysis indicates that the drip shield can withstand direct impacts. Consequently, the additional mechanical stability provided by backfill will only aid in the level of conservatism of design.

Because of the design of the drip shield and the waste packages, there does not appear to be a credible mechanism for rockfall to breach the drip shield or the waste packages. Because no mechanism from cave-ins exists to breach these components, no mechanism from cave-ins is present for the release of radionuclides, and, consequently, dose is not significantly changed. Therefore, this FEP is *Excluded* based on low consequence to dose.

Primary FEP: Rockfall (Large Block)
Secondary FEP: Roof falls

FEP Number: 2.1.07.01.04	**Originator FEP Description**: Instability of the disturbed rock zone could lead to localized roof falls in the first few hundred years. etc. (WIPP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* This FEP is construed to be similar to the Primary FEP Description.

***Discussion**:* See discussion for Primary FEP

Primary FEP: Mechanical Degradation or Collapse of Drift

FEP Number: **2.1.07.02.00**	**Primary 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. Rockfall of small blocks may produce rubble throughout part or all of the drifts.
Primary Assigned to: Disruptive Events FEPs, Engineered Barrier Systems FEPs	
Screening Decision: *Excluded* from the TSPA-SR *(Preliminary)*	**Screening Decision Basis**: Low consequence to dose
Number of Secondaries: *8* **Screening Decisions:** All *Excluded* from the TSPA-SR	

Geologic Process: Drift degradation due to seismicity and thermal effects.

Potential Consequences: This FEP is distinguishable from the Primary FEP "Rockfall (large block)" (2.1.07.02.00) with regards to the collapse of drifts as opposed to damage caused by individual key blocks. The potential damage may not be directly related to impact of a large key block on the drip shield but rather to impaired performance due to the accumulation of multiple small blocks (rubble) in the drift with time. For example, the presence of the rubble may alter thermal characteristics in the EBS, if sufficient rubble collects around the drift shield, or alter effects at the base of the drip shield. The proximal cause of the small-block accumulation, however, is identical with that of "Rockfall." With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. A triggering event may cause movement or fall of small blocks, and the drift collapse could affect stability of the EBS and waste packages, and lead to rubble accumulating in parts of the drift.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. Stress regimes as described by Savage et al. 1999.

Discussion: The various repository designs (CRWMS M&O 1999a, p. 4-16 and 4-17 and CRWMS M&O 2000b) include a drip shield. A calculation of the potential for rockfall to cause damage to the drip shield is presented in CRWMS M&O (2000t). The analysis indicates that no cracks develop in the drip shield due to the dynamic impact of a rock on the drip shield for an effective rock mass of up to 10 MT over a 3-m length of drip shield. Breaching of the drip shield by small key block rockfall is, therefore, *Excluded.*

The analysis in CRWMS M&O (2000j) also provides the number and size distribution of key blocks that are likely to occur. As shown in Table 3 in Section 6.2.17, rockfall of any type is an infrequent event, with the maximum density of rockfalls of 32 per km of drift, and with 75 percent of the key blocks being of 0.24 m^3 or less (CRWMS M&O 2000j, Tables 12 and 15). In some instances, the key-block density is as little as 2 per km. Consequently, concerns with rubble build-up will lead to stability issues and/or thermal build-up are not credible.

The presence of the drip shield precludes "Mechanical degradation or collapse of drift" as a credible scenario contributing to direct waste-package breaching or damage. Also, the accumulation of significant rubble or collapse of drifts does not appear to be a credible event. If no damage to the waste package occurs, or if there is no significant change to the drift characteristics due to a scarcity of rockfalls of small-blocks, there is no mechanism for drift degradation or collapse to result in a radionuclide release, or for increasing or significantly changing the calculated dose. Consequently, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Mechanical Degradation or Collapse of Drift (continued)

Relation of Elements of the Primary FEP Description to Secondary FEPs	
Partial or complete collapse of drifts	Stability (in waste and EBS) (2.1.07.02.01)
Seismic activity, thermal effects, stresses related to excavation or other mechanisms	Mechanical (events and process in the waste and EBS) (2.1.07.02.02) Mechanical failure or repository (2.1.07.02.05) Creeping of rock mass (2.1.07.02.08)
Stability of engineered barriers and waste packages	Subsidence/collapse (2.1.07.02.06) Vault collapse (2.1.07.02.07)
Drift collapse may be localized	Rockfall stopes up fault (2.1.07.02.03)
Rockfall of small blocks may produce rubble	Rockfall (rubble) (in waste and EBS) (2.1.07.02.04)

References: 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 (CRWMS M&O 2000i) for the design including backfill (*License Application Design Selection Report* B00000000-01717-1705-00011 CRWMS M&O 1999a, pp. 4-16 and 4-17), and it incorporates the results of a supporting calculation (*Supporting Calculation for Drift Degradation* CAL-EBS-MD-000010 CRWMS M&O 2000j) for a no-backfill design with drip shield, with drifts reoriented to azimuth 75. The impact of Rock Fall on the drip shield is discussed in *Rock Fall on Drip Shield*, CAL-EDS-ME-000001 (CRWMS M&O 2000t).

Links to FEPs that examine related but distinct consequences and events

Tectonic activity — large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Seismic activity (1.2.03.01.00)
Rock properties of host rock and other units (2.2.03.02.00)

Links to FEPs that examine similar consequences and events

Mechanical failure of cladding (2.1.02.24.00)
Mechanical impact on waste container and drip shield (2.1.03.07.00)
Effects and degradation of drip shield (2.1.06.06.00)
Mechanical degradation or collapse of drift (2.1.07.02.00)
Thermally induced stress changes in waste and EBS (2.1.11.07.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME3: Thermal-Mechanical Effects

Integrated Subissues / Related Subissues:

ENG1: Degradation of Barriers / TEF2, ENFE2, CLST1, CLST2, CLST6
ENG2: Mechanical Disruption of Barriers / CLST1, CLST 2, CLST6, SDS2, SDS3, SDS4, RDTME2
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS2, SDS3

Primary FEP: Mechanical Degradation or Collapse of Drift (continued)

Primary FEP: **Mechanical Degradation or Collapse of Drift**
Secondary FEP: Stability (in the waste and EBS)

FEP Number: 2.1.07.02.01	**Originator FEP Description**: The stability of the vault and its contents may undergo substantial changes over time. (AECL)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Although the FEP description is not specific, this FEP is construed to imply concern with the mechanical integrity of the drift (or vault as mentioned in the description). The potential damage may not be directly related to impact of a large key block on the drip shield but rather to impaired performance due to the accumulation of multiple small blocks (rubble) in the drift with time. For example, the presence of the rubble may alter thermal characteristics in the EBS, if sufficient rubble collects around the drift shield, or alter thermal or hydrologic effects at the base of the drip shield. The proximal cause of the small-block accumulation, however, is identical with that of "Rockfall." With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. A triggering event may cause movement or fall of small blocks, and the drift collapse could affect stability of the EBS and waste packages, leading to rubble accumulating in parts of the drift.

Discussion: The various repository designs (CRWMS M&O 1999a, p. 4-16 and 4-17 and CRWMS M&O 2000b) include a drip shield. A calculation of the potential for rockfall to cause damage to the drip shield is presented in CRWMS M&O (2000t). The analysis indicates that no cracks develop in the drip shield due to the dynamic impact of a rock on the drip shield for an effective rock mass of up to 10 MT over a 3-m length of drip shield. Breaching of the drip shield by small key-block rockfall is, therefore, *Excluded*.

The analysis in CRWMS M&O (2000j) also provides the number and size distribution of key blocks that are likely to occur. As shown in Table 3 in Section 6.2.17, rockfall of any type is an infrequent event, with the maximum density of rockfalls of 32 per km of drift, with 75 percent of the key blocks being of 0.24 m^3 or less (CRWMS M&O 2000j, Tables 12 and 15). In some instances, the key-block density is as little as 2 per km. Consequently, concerns with rubble build-up will lead to stability issues and/or thermal build-up are not credible.

The presence of the drip shield precludes "Mechanical degradation or collapse of drift" as a credible scenario contributing to direct waste-package breaching or damage. Also, the accumulation of significant rubble or collapse of drifts does not appear to be a credible event. If no damage to the waste packages occurs, or if there is no significant change to the drift characteristics due to a scarcity of small-block rockfalls, there is no mechanism for drift degradation or collapse to result in a radionuclide release or for increasing or significantly changing the calculated dose. Consequently, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Mechanical Degradation or Collapse of Drift (continued)

Primary FEP: Mechanical Degradation or Collapse of Drift
Secondary FEP: Mechanical (events and process in the waste and EBS)

FEP Number: 2.1.07.02.02	**Originator FEP Description**: (none) (NEA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is undefined and is construed to be identical with the Primary FEP. The potential damage may not be directly related to impact of a large key block on the drip shield but rather to impaired performance due to the accumulation of multiple small blocks (rubble) in the drift with time. For example, the presence of the rubble may alter thermal characteristics in the EBS, if sufficient rubble collects around the drift shield, or alter thermal or hydrologic effects at the base of the drip shield. The proximal cause of the small-block accumulation, however, is identical with that of "Rockfall." With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. A triggering event may cause movement or fall of small blocks, and the drift collapse could affect stability of the EBS and waste packages, leading to rubble accumulating in parts of the drift.

Discussion: See Primary FEP

Primary FEP: Mechanical Degradation or Collapse of Drift (continued)

Primary FEP: Mechanical Degradation or Collapse of Drift
Secondary FEP: Rockfall stopes up fault

FEP Name 2.1.07.02.03	Originator FEP Description: Rockfall preferentially stopes up a fault which has intersected a repository. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	Screening Decision Basis: Low consequence to dose

Potential Consequences: This FEP is concerned with the focusing of rockfall events in the vicinity of faults. Even if the rockfall were to be focused, the impact to the repository would be identical to the effects resulting from a more-evenly distributed degradation of the drift. The potential damage may not be directly related to impact of a large key block on the drip shield but rather to impaired performance due to the accumulation of multiple small blocks (rubble) in the drift with time. For example, the presence of the rubble may alter thermal characteristics in the EBS, if sufficient rubble collects around the drift shield, or alter thermal or hydrologic effects at the base of the drip shield. The proximal cause of the small-block accumulation, however, is identical with that of "Rockfall." With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. A triggering event may cause movement or fall of small blocks in the vicinity of the fault, and the drift collapse could affect stability of the EBS and waste packages, and lead to rubble accumulating in parts of the drift.

Discussion: Displacements along existing faults and fractures within the repository, which might be detrimental to the physical integrity of system components, will either be of low magnitude (USGS 1998) or will be addressed by a repository design that requires the use of 60-m set-backs from block-bounding faults. Additionally, site observations indicate that the width of the zone of influence on fracture frequency in the immediate vicinity of a fault is, in general, quite narrow, ranging from less than 1 m to about 7 m from the fault and correlates, in a general way, with the amount of cumulative fault offset. The width of the zone of influence around a fault does not appear to be related to depth. Consequently, zones that are most subject to fault stoping will be avoided by set-backs, and other fault zones involve a minimal area on either side of the fault where, and if, it crosses the drift.

The amount of deformation associated with faults appears, in part, to be dependent upon which lithologic unit is involved in the faulting. Lithostratigraphic controls also affect fracture spacing, type, number of fracture sets, continuity of individual fractures within each lithostratigraphic zone, and they also affect the fracture connectivity of the network as a whole. Consequently, in as much as fault-fracture relationships are represented in the available data used as the basis for analyzing rockfall, the results of the analysis reflect the consequent effects of focused rockfall in the vicinity of faults.

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 (CRWMS M&O 2000i) for the design including backfill (CRWMS M&O 1999a, pp. 4-16 and 4-17), and it incorporates the results of a supporting calculation (CRWMS M&O 2000j) for a no-backfill design with reoriented drifts (CRWMS M&O 2000b). The analysis used information on existing joint sets and then randomly generates additional joint planes. The joint-and-fracture data was varied by lithologic unit in the analyses.

The analysis in CRWMS M&O (2000j) also provides the number and size distribution of key blocks that are likely to occur. As shown in Table 3 in Section 6.2.17, rockfall of any type is an infrequent event, with the maximum density of rockfalls of 32 per km of drift, and with 75 percent of the key blocks being of 0.24 m^3 or less (CRWMS M&O 2000j, Tables 12 and 15). In some instances, the key-block density is as little as 2 per km. Consequently, concerns with rubble build-up will lead to stability issues and/or thermal build-up are not credible. If, as site observations suggest, the zone of fault stoping would be limited to a few meters, then the build-up of rubble would not be significant to repository performance due to the minimal area of the repository affected.

Because repository performance is not significantly affected, then drift degradation or collapse does not provide a mechanism to significantly change the dose. Consequently, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Mechanical Degradation or Collapse of Drift (continued)

Primary FEP: Mechanical Degradation or Collapse of Drift
Secondary FEP: Rockfall (rubble) (in waste and EBS)

FEP Name 2.1.07.02.04	**Originator FEP Description**: After the thermal period, it expected that rock around the drifts, no longer in thermal compression, will begin to relax into the drifts, filling them and causing container damage. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose
Potential Consequences: This FEP is construed to be identical with the Primary FEP. The potential damage may not be directly related to impact of a large key block on the drip shield but rather to impaired performance due to the accumulation of multiple small blocks (rubble) in the drift with time. For example, the presence of the rubble may alter thermal characteristics in the EBS, if sufficient rubble collects around the drift shield, or alter thermal or hydrologic effects at the base of the drip shield. The proximal cause of the small-block accumulation, however, is identical with that of "Rockfall." With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. A triggering event may cause movement or fall of small blocks, and the drift collapse could affect stability of the EBS and waste packages, and lead to rubble accumulating in parts of the drift. ***Discussion:*** See Primary FE	

Primary FEP: Mechanical Degradation or Collapse of Drift
Secondary FEP: Mechanical failure of repository

FEP Name 2.1.07.02.05	**Originator FEP Description**: Mechanical rupture of the repository may occur due to sudden changes in stress, e.g., earthquakes, etc., and due to slow motions (creep) in the rockmass, e.g., loading-unloading and plate motions. etc. (Joint SKI/SKB)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose
Potential Consequences: With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. This deterioration may be related to a triggering event (such as an earthquake) that may cause movement or fall of small blocks, and the drift collapse could affect stability of the EBS and waste packages, and lead to rubble accumulating in parts of the drift. Alternatively, it could result from generalized slow motion (creep) in response to changes in the state of stress. Plate-motion effects are only indirectly linked to the FEP in as much as they correspond to regional tectonic activity that leads to seismic activity in the region. The presence of the rubble in the drift may alter thermal characteristics in the EBS and affect component performance and/or water may flow through tears or ruptures to transport the radionuclides from the repository. ***Discussion***: Creep will likely be reflected in the failing of small blocks with the repository drifts. 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 (CRWMS M&O 2000i) for the design including backfill (CRWMS M&O 1999a, pp. 4-16 and 4-17), and it incorporates the results of a supporting calculation (CRWMS M&O 2000j) for a no-backfill design with reoriented drifts (CRWMS M&O 2000b). The current design (CRWMS M&O 2000b) includes a drip shield and drifts oriented along azimuth 252. The analysis in CRWMS M&O (2000j) provides the number and size distribution of key blocks that are likely to occur. As shown in Table 3 in Section 6.2.17, rockfall of any type is an infrequent event, with the maximum density of rockfalls of 32 per km of drift, and with 75 percent of the key blocks being of 0.24 m^3 or less (CRWMS M&O 2000j, Tables 12 and 15). In some instances, the key-block density is as little as 2 per km. Consequently, concerns with rubble build-up will lead to stability issues and/or thermal build-up are not credible. If, as site observations suggest, the zone of fault stoping would be limited to a few meters, then the build-up of rubble would not be significant to repository performance due to the minimal area of the repository affected. Because repository performance is not significantly affected, then drift degradation or collapse does not provide a mechanism to significantly change the dose. Consequently, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.	

Primary FEP: Mechanical Degradation or Collapse of Drift (continued)

Primary FEP: Mechanical Degradation or Collapse of Drift
Secondary FEP: Subsidence/collapse

FEP Name 2.1.07.02.06	**Originator FEP Description**: (none) (NEA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is undefined and is construed to be identical with the Primary FEP. With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. A triggering event may cause movement or fall of small blocks, and the drift collapse could affect stability of the EBS and waste packages, and lead to rubble accumulating in parts of the drift. The presence of the rubble may alter thermal characteristics in the EBS and affect component performance and/or water may flow through tears or ruptures to transport the radionuclides from the repository.

Discussion: See Primary FEP

Primary FEP: Mechanical Degradation or Collapse of Drift
Secondary FEP: Vault collapse

FEP Name 2.1.07.02.07	**Originator FEP Description**: The only means of support for the vaults (besides its natural strength given by its shape) are likely to be shotcrete/mesh and rock-bolts which prestress the roof arch. These supports have a limited lifespan, after which the cavern roof will be unsupported and may collapse creating an extensive disturbed zone. etc. (UK-HMIP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. A triggering event may cause movement or fall of small blocks, and the drift collapse could affect stability of the EBS and waste packages, and lead to rubble accumulating in parts of the drift. The presence of the rubble may alter thermal characteristics in the EBS and affect component performance, and/or water may flow through tears or ruptures to transport the radionuclides from the repository.

Discussion: 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 (CRWMS M&O 2000i) for the design including backfill (CRWMS M&O 1999a, pp. 4-16 and 4-17), and it incorporates the results of a supporting calculation (CRWMS M&O 2000j) for a no-backfill design with reoriented drifts (CRWMS M&O 2000b). The current design (CRWMS M&O 2000b) includes a drip shield and drifts oriented along azimuth 252. The analyses did not consider any beneficial effects of drift and rock supports and are, therefore, conservative with regard to this FEP.

The analysis in CRWMS M&O (2000j) provides the number and size distribution of key blocks that are likely to occur. As shown in Table 3 in Section 6.2.17, rockfall of any type is an infrequent event, with the maximum density of rockfalls of 32 per km of drift, and with 75 percent of the key blocks being of 0.24 m^3 or less (CRWMS M&O 2000j, Tables 12 and 15). In some instances, the key-block density is as little as 2 per km. Consequently, concerns with rubble build-up will lead to stability issues and/or thermal build-up are not credible events. If as site observation suggests, the zone of fault stoping would be limited to a few meters, the build-up of rubble would not be significant to repository performance due to the minimal area of the repository affected.

Because repository performance is not significantly affected, then drift degradation or collapse does not provide a mechanism to significantly change the dose. Consequently, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Mechanical Degradation or Collapse of Drift (continued)

Primary FEP: Mechanical Degradation or Collapse of Drift
Secondary FEP: Creeping rock mass

FEP Name 2.1.07.02.08	Originator FEP Description: Creeping of rock mass may occur in connection with excavation due to stress changes. These changes create an unstable situation in the rock mass close to the repository. However, this effect is probably of minor importance. etc. (Joint SKI/SKB)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: With time and with changes in the state of stress (due to stress relief, seismic activity, tectonic activity, or thermal loading and unloading), the rock mass surrounding the emplacement drifts will deteriorate. This deterioration may be could result from generalized slow motion (creep) in response to changes in the state of stress. The relief of this condition results in the presence of the rubble in the drift that may alter thermal characteristics in the EBS and affect component performance and/or water may flow through tears or ruptures to transport the radionuclides from the repository.

Discussion: Creep will likely be reflected in the failing of small blocks with the repository drifts. 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 (CRWMS M&O 2000i) for the design including backfill (CRWMS M&O 1999a, pp. 4-16 and 4-17), and it incorporates the results of a supporting calculation (CRWMS M&O 2000j) for a no-backfill design with reoriented drifts (CRWMS M&O 2000b). The current design (CRWMS M&O 2000b) includes a drip shield and drifts oriented along azimuth 252.

The analysis in CRWMS M&O (2000j) provides the number and size distribution of key blocks that are likely to occur. As shown in Table 3 in Section 6.2.17, rockfall of any type is an infrequent event, with the maximum density of rockfalls of 32 per km of drift, and with 75 percent of the key blocks being of 0.24 m^3 or less (CRWMS M&O 2000j, Tables 12 and 15). In some instances, the key-block density is as little as 2 per km. Consequently, concerns with rubble build-up will lead to stability issues and/or thermal build-up are not credible.

Because repository performance is not significantly affected, then drift degradation or collapse does not provide a mechanism to significantly change the dose. Consequently, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock

FEP Number:	Primary FEP Description:
2.2.06.01.00	Changes in stress due to all causes, including heating, seismic activity, and regional tectonic activity, have a potential [to] result in strains that affect flow properties in rock outside the excavation-disturbed zone. See also FEPs 2.2.01j and 2.2.01w for discussion of excavation-related stress changes and FEPs 2.2.10t and 2.2.01ar for thermo-mechanical-relates stress changes.

Primary Assigned to: Disruptive Events FEPs, Near Field Environment FEPs.

Screening Decision: *Excluded* from the TSPA-SR *(Preliminary)*	**Screening Decision Basis**: Low consequence to dose

Number of Secondaries: *10* **Screening Decisions**: All *Excluded* from the TSPA-SR

Geologic Process: Tectonism / Seismicity

Potential Consequences: Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. The focus of this FEP is on changes that might have the potential to affect flow-and-transport properties outside of the drifts. Changes in flow have the potential to change the dose.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The peak phase of tectonism took place 12 to 11.6 Ma.

Discussion: Changes in stresses, regardless of the proximal cause, may result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The effects of changes to fracture systems 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 2000e). The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) was examined because several fracture properties (permeability, capillary pressure, and porosity) are a function of fracture aperture. The matrix, on the other hand, has much greater porosity than the fractures in general, and its properties are not expected to be as sensitive to mechanical strain. The results of the analysis indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture. Because transport properties in the UZ are not significantly affected, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, effects of changes in stress are *Excluded* from the TSPA-SR based on low consequence to dose.

Relation of Elements of Primary Description to Secondary FEPs	
Changes in stress: heating, seismic activity, and regional tectonic activity	Regional stress regime (2.2.06.01.04) Regional stress regime (2.2.06.01.05) Regional stress regime (2.2.06.01.06) Stress field (in geosphere) (2.2.06.01.07) Changes in stress field (2.2.06.01.08) Changes in regional stress (2.2.06.01.09) Stress changes - hydrogeologic effects (2.2.06.01.10)
Affect flow properties in rock outside the excavation-disturbed zone	Stress-produced porosity changes (2.2.06.01.01) Stress-produced permeability changes (2.2.06.01.02) Stress-produced permeability changes (2.2.06.01.03) Stress field (in geosphere) (2.2.06.01.07) Stress changes - hydrogeologic effects (2.2.06.01.10)

References: *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000e), *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa, Section 6.3.2). See also *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000q) and *Features, Events, and Processes in SZ Flow and Transport* ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock (continued)

Links to FEPs that examine related but distinct effects and consequences
Tectonic activity—large scale (1.2.01.01.00) Fractures (1.2.02.01.00) Faulting (1.2.02.02.00) Igneous activity causes changes to rock properties (1.2.04.02.00) Hydrologic response to seismic activity (1.2.10.01.00) Hydrologic response to igneous activity (1.2.10.02.00) Excavation and construction-related changes in the adjacent host rock (2.2.01.01.00) Thermal and other waste and Engineered Barrier System (EBS) related changes in the adjacent host rock (2.2.01.02.00) Thermo-mechanical alteration of fractures near repository (2.2.10.04.00) Thermo-mechanical alteration of rocks above and below the repository (2.2.10.05.00)
Links to FEPs that examine similar effects and consequences
Water-table rise (1.3.07.02.00) Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults (2.2.06.02.00) Changes in stress (due to seismic or tectonic effects) alter perched water zones (2.2.06.03.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS1: Faulting
SDS2: Seismicity
SDS3: Fractures

Integrated Subissues / Related Subissues:

UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock (continued)

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock**
Secondary FEP: Stress-produced porosity change

FEP Number: **2.2.06.01.01**	**Originator FEP Description:** Tectonic and seismic events alter porosity on a site-scale. (YMP).
Screening Decision: *Excluded* from the TSPA-SR	***Screening Decision Basis:*** Low consequence to dose

Potential Consequences: Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. The focus of this FEP is specifically on changes to porosity that might have the potential to affect flow-and-transport properties. Changes in flow have the potential to change the dose.

Discussion: Changes in stresses, regardless of the proximal cause (e.g., seismicity, tectonism, faulting, heating) may result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The porosity of the matrix, on the other hand, is not expected to be as sensitive to mechanical strain. The effects of changes to fracture systems 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 2000e). The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) was examined because several fracture properties (permeability, capillary pressure, and porosity) are a function of fracture aperture. The results of the analysis indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture. Because transport properties in the UZ are not significantly affected, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, effects of changes in stress are *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock**
Secondary FEP: Stress-produced permeability changes

FEP Number: **2.2.06.01.02**	**Originator FEP Description:** Tectonic and seismic events alter permeability on a site-scale. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. The focus of this FEP is specifically on changes to permeability that might have the potential to affect flow-and-transport properties. Changes in flow have the potential to change the dose.

Discussion: Changes in stresses, regardless of the proximal cause (e.g., seismicity, tectonism, faulting, heating) may result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The permeability of the matrix, on the other hand, is not expected to be as sensitive to mechanical strain. The effects of changes to fracture systems 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 2000e). The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) was examined because several fracture properties (permeability, capillary pressure, and porosity) are a function of fracture aperture. The results of the analysis indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture. Because transport properties in the UZ are not significantly affected, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, effects of changes in stress are *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock (continued)

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock
Secondary FEP: Stress-produced permeability changes

FEP Number: 2.2.06.01.03	**Originator FEP Description**: Tectonic events alter permeability on a site-scale (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

***Discussion**:* This FEP is nearly identical to secondary FEP 2.2.06.01.02. The only difference is the deletion of seismic events being a proximal cause. As previously discussed, the proximal cause of the change of stress is not critical to the sensitivity analysis used to examine the effect of stress changes. See the preceding discussion.

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock
Secondary FEP: Regional Stress Regime

FEP Numbers: 2.2.06.01.04, 2.2.06.01.05, 2.2.06.01.06	**Originator FEP Description**: Estimates for the orientation of regional stress field in the crystalline basement of Northern Switzerland, as derived from seismotectonics and from in-situ measurements, are approximately the same: a NW-SE direction for the horizontal component of the principal stress (sH).[A discussion continues about inferences and uses of the measurements). (NAGRA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* The FEP description pertains to estimates for the regional stress field in Switzerland and is not directly applicable to Yucca Mountain. The FEP Descriptions for Secondary FEPs 2.2.06.01.04, 2.2.06.01.05, and 2.2.06.01.05 are identical, so are not discussed separately (Source identifier codes are K5.14, K6.14, and K7.10, respectively). This FEP was construed to be potentially applicable to Yucca Mountain with regards to the potential for changes in the stress regime. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose.

Discussion: Changes in stresses, regardless of the proximal cause (e.g., seismicity, tectonism, faulting, heating) may result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The matrix properties, on the other hand, are not expected to be as sensitive to mechanical strain. The effects of changes to fracture systems 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 2000e). The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) was examined because several fracture properties (permeability, capillary pressure, and porosity) are a function of fracture aperture. The results of the analysis indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture. Because transport properties in the UZ are not significantly affected, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, effects of changes in stress are *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock (continued)

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock**
Secondary FEP: Stress field (in geosphere)

FEP Number: **2.2.06.01.07**	**Originator FEP Description**: The crystalline bedrock deforms according to the acting stress field and its inherent strength. Changes in the groundwater flow and changes in the temperature field will change the active stress acting on the rock which in turn will change the fracture properties and thereby the groundwater flow. (SKI)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

***Potential Consequences**:* The FEP description pertains to estimates for the regional stress field at a site other than Yucca Mountain and is not directly applicable to Yucca Mountain. However, changes in groundwater flow and changes in temperature can result in a change in the state of active stress. Accordingly, this FEP was construed to be potentially applicable to Yucca Mountain with regards to the potential for changes in the stress regime. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose.

Discussion: Changes in stresses, regardless of the proximal cause (e.g., seismicity, tectonism, faulting, heating) may result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The permeability of the matrix, on the other hand, is not expected to be as sensitive to mechanical strain. The effects of changes to fracture systems 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 2000e). The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) was examined because several fracture properties (permeability, capillary pressure, and porosity) are a function of fracture aperture. The results of the analysis indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture. Because transport properties in the UZ are not significantly affected, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, effects of changes in stress are *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock (continued)

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock**
Secondary FEP: Changes in stress field

FEP Number: 2.2.06.01.08	**Originator FEP Description**: Salt creep will lead to changes in the stress field, compaction of the waste and containers, and consolidation of the long-term components of the sealing system. etc. (WIPP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Salt-creep issues are not specifically applicable because the repository in being constructed in volcanic tuff. This FEP deals specifically with the compaction of waste, containers, and consolidation of the long-term components of the sealing system. This FEP was construed to be potentially applicable through the mechanism of stress change. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: The disruptive events mentioned in the FEP description (i.e., compaction and consolidation) require the creeping of the drift walls onto the system components. The material properties of volcanic tuffs, however, are significantly different from salt. The volcanic tuffs will not creep as much as salt deposits. This is one of the multiple reasons for selecting Yucca Mountain for further study rather than other potential repository sites in salt deposits.

The effects of changes to the fracture systems 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 2000e). The effect of changes in fracture apertures (0.2 times to 10 times the existing 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. Therefore, effects on the UZ are *Excluded* from the TSPA-SR

Because the mechanisms leading to compaction and consolidation are not credible at Yucca Mountain, and other related effects are of low consequences to dose, this FEP is *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock**
Secondary FEP: Changes in regional stress

FEP Number: 2.2.06.01.09	**Originator FEP Description**: The tectonic setting and structural features of the area around the WIPP have been characterized [. . .]. In summary, there is no geological evidence for Quaternary regional tectonics in the Delaware Basin. etc. (WIPP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP description is specific to the Waste Isolation Pilot Project (Source identifier is W1.003). This FEP was construed to be applicable through the mechanism of stress change. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: See Primary FEP Discussion.

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock (continued)

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Change Porosity and Permeability of Rock
Secondary FEP: Stress-changes - hydrogeologic effects

FEP Number: **2.2.06.01.10**	**Originator FEP Description**: During seismic activity, movement occurs along various faults. This results in stress changes in the intervening rock blocks - e.g., a stress relief in the direction parallel to the fault. The principle effect in a hard rock is to change the aperture of various openings in the rock. (NAGRA)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is specifically concerned with the transfer of stress from block-bounding faults to the intervening rock blocks, resulting in changes to the apertures of various openings in the rock. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: Changes in stresses, regardless of the proximal cause, may result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The effects of changes to fracture systems 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 2000e). The effect of changes in fracture apertures (0.2 times to 10 times the existing 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 (and hence on dose) in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture.

Because there is no significant change in transport in the UZ, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, stress-change is *Excluded* from the TSPA-SR .

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults

FEP Number: 2.2.06.02.00	**Primary FEP Description:** Stress changes due to thermal, tectonic and seismic processes result in strains that alter the permeability along and across faults.
Primary Assigned to: Disruptive Events FEPs, Unsaturated Zone FEPs, Saturated Zone FEPs	
Screening Decision: *Excluded* from the TSPA-SR *(Preliminary)*	**Screening Decision Basis**: Low consequence to dose
Number of Secondaries: *5* **Screening Decisions***:* All *Excluded* from the TSPA-SR	

Geologic Process: Tectonism or Seismicity. The FEP is not process-specific

Potential Consequences: This FEP is concerned with the effects of stress changes on permeability along and across faults. Changes in stress due to all causes have the potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The peak phase of tectonism took place 12 to 11.6 Ma. The width of the zone of influence on fracture frequency in the immediate vicinity of a fault is, in general, quite narrow, ranging from less than 1 m to about 7 m from the fault and correlates, in a general way, with the amount of cumulative fault offset. The width of the zone of influence around a fault does not appear to be related to depth. The amount of deformation associated with faults appears, in part, to be dependent upon which lithologic unit is involved in the faulting. Lithostratigraphic controls affect fracture spacing, type, number of fracture sets, continuity of individual fractures within each lithostratigraphic zone, and also the fracture connectivity of the fracture network as a whole.

Discussion: The effects of changes to fault systems 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 2000e, Section 6.7.8). The analysis specifically addresses the effects of stress changes on permeability along and across faults only.

The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) in fault zones was examined because several fracture properties (permeability, capillary pressure, and porosity) are functions of fracture aperture (CRWMS M&O 2000e). The permeability of the matrix, on the other hand, is not expected to be as sensitive to mechanical strain. The results indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ (CRWMS M&O 2000e, Section 7).

Because there is no significant change in transport in the UZ, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, stress change is *Excluded* from the TSPA-SR.

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults

Relation of Elements of Primary Description to Secondary FEPs	
Stress changes	Aseismic alteration or permeability along and across faults (2.2.06.02.01) Relaxation of thermal stress by fault movement (2.2.06.02.03) Seismically-stimulated release of thermo-mechanical stress on bounding faults (2.2.06.02.04) Relaxation of thermal stresses by fault movement (2.2.06.02.05)
Altered permeability along and across faults.	Aseismic alteration or permeability along and across faults (2.2.06.02.01) Fracture dilation along faults creates zones of enhanced permeability (2.2.06.02.02)

References: *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000e), *Dike Propagation Near Drifts* ANL-WIS-MD-000015 (CRWMS M&O 2000aa, Section 6.3.2), *Effects of Fault Displacement on Emplacement Drifts* ANL-EBS-GE-000004 (CRWMS M&O 2000s). See also *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001 (CRWMS M&O 2000q) and *Features, Events, and Processes in SZ Flow and Transport* ANL-NBS-MD-000002 (CRWMS M&O 2000r)

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults (continued)

Links to FEPs that examine related but distinct effects and consequences

Tectonic activity—large scale (1.2.01.01.00)
Fractures (1.2.02.01.00)
Faulting (1.2.02.02.00)
Igneous activity causes changes to rock properties (1.2.04.02.00)
Hydrologic response to seismic activity (1.2.10.01.00)
Hydrologic response to igneous activity (1.2.10.02.00)

Links to FEPs that examine similar effects and consequences

Changes in stress (Due to Thermal, Seismic, or Tectonic Effects) change porosity and permeability of rock (2.2.06.01.00)
Changes in stress (due to seismic or tectonic effects) alter perched water zones (2.2.06.03.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS1: Faults
SDS3: Fractures
USFIC3: Shallow Infiltration
USFIC4: Deep Percolation

Integrated Subissues / Related Subissues:

ENG3: Quantity and Chemistry of Water Contacting the Waste Package and Waste Form / ENFE1, ENFE2, CLST1, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS2
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3, SDS4
Direct 1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, IA1, IA2, SDS4

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults (continued)

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults**
Secondary FEP: Aseismic alteration of permeability along and across faults

FEP Number: 2.2.06.02.01	Originator FEP Description: Aseismic stress changes due to tectonic events alter the permeability along and across faults. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is focused on aseismic stress changes altering the permeability along faults. Changes in stress due to all causes (seismic or aseismic) have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: The effects of changes to fault systems 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 2000e). The analysis specifically addresses the effects of stress changes on permeability in the vicinity of faults only.

The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) in fault zones was examined because several fracture properties (permeability, capillary pressure, and porosity) are functions of fracture aperture (CRWMS M&O 2000e). The permeability of the matrix, on the other hand, is not expected to be as sensitive to mechanical strain. The results indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ (CRWMS M&O 2000e, Section 7).

Because there is no significant change in transport in the UZ, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, aseismic stress-change is *Excluded* from the TSPA-SR .

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults (continued)

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults**
Secondary FEP: Fracture dilation along faults creates zones of enhanced permeability

FEP Number: **2.2.06.02.02**	**Originator FEP Description**: Fracture dilation along faults creates zones of enhanced permeability in the Calico Hills and Paintbrush nonwelded units. Erosion of an arroyo at the surface and increased hydraulic conductivity of the Paintbrush unit create a zone of increased percolation along the fault. Moisture moves through fractures along the fault. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP is specifically concerned with fracture dilation along faults coupled with surface erosion that focuses surface flow such that increased infiltration occurs along fault zones. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: The first concern of this FEP, fracture dilation along fault zones, has been examined. The effects of changes to fault systems 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 2000e). Changes in stresses, regardless of the proximal cause, may result in changes to the hydrologic characteristics of faults, as expressed in the parameter of fracture aperture. The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) in fault zones was examined because several fracture properties (permeability, capillary pressure, and porosity) are functions of fracture aperture (CRWMS M&O 2000e). The results indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ (CRWMS M&O 2000e, Section 7).

Because there is no significant change in transport in the UZ, changes in the state of stress do not provide a mechanism that could significantly change the dose, and there is no mechanism present that significantly changes dose due to fracture dilation alone. Therefore, the fracture dilation component of this FEP is *Excluded* from the TSPA-SR .

The second concern of this FEP, focusing of surface flow such that increased infiltration occurs along fault zones, is not *Excluded* on the results of the above analysis. However, climate changes, which also affect the infiltration rates is *Included* in the TSPA-SR. The issue of infiltration and changes in surface conditions (rather the fracture dilation) are the controlling factor. Infiltration and other surface effects are dealt with as Primary FEPs in the *Features, Events, and Process in the Unsaturated Zone* (CRWMS M&O 2000q).

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults (continued)

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults**
Secondary FEP: Relaxation of thermal stresses by fault movement

FEP Number: 2.2.06.02.03	**Originator FEP Description:** Thermo-mechanical stress buildup in the mountain may produce movement on adjacent faults. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: This FEP starts with a presumption that the thermo-mechanical response of the mountain to repository heating may be movement on adjacent faults. Accepting this premise only for the basis of discussion, the consequence of concern it that the change in stress along fault zones alters the flow properties of faults, including permeability of faults. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: The effects of changes to fault systems 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 2000e). The analysis specifically addresses the effects of stress changes on permeability along and across faults only.

The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) in fault zones was examined because several fracture properties (permeability, capillary pressure, and porosity) are functions of fracture aperture (CRWMS M&O 2000e). The permeability of the matrix, on the other hand, is not expected to be as sensitive to mechanical strain. The results indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ (CRWMS M&O 2000e, Section 7).

Because there is no significant change in transport in the UZ, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, a thermo-mechanical stress-change is *Excluded* from the TSPA-SR .

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults (continued)

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults**

Secondary FEP: Seismically-stimulated release of thermo-mechanical stress on bounding faults

FEP Number: 2.2.06.02.04	**Originator FEP Description**: Thermal-mechanical stress accumulated as a result of repository heat is stimulated by seismic waves to be released on nearby faults. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: This FEP starts with a presumption that the thermo-mechanical response of the mountain to repository heating may be movement on adjacent faults or seismic activity along adjacent faults. Accepting this premise only for the basis of discussion, the consequence of concern it that the change in stress along fault zones alters the flow properties of faults, including permeability of faults. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: The effects of changes to fault systems 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 2000e). The analysis specifically addresses the effects of stress changes on along and across faults only.

The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) in fault zones was examined because several fracture properties (permeability, capillary pressure, and porosity) are functions of fracture aperture (CRWMS M&O 2000e). The properties of the matrix, on the other hand, are not expected to be as sensitive to mechanical strain The results indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ (CRWMS M&O 2000e, Section 7).

Because there is no significant change in transport in the UZ, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, thermo-mechanical stress-change is *Excluded* from the TSPA-SR .

Primary FEP: Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults (continued)

Primary FEP: **Changes in Stress (Due to Thermal, Seismic, or Tectonic Effects) Produce Change in Permeability of Faults**
Secondary FEP: Relaxation of thermal stresses by fault movement

FEP Number: **2.2.06.02.05**	**Originator FEP Description:** Thermal-mechanical stress buildup in the mountain may produce movement on adjacent faults. (YMP)
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis:** Low consequence to dose

Potential Consequences: This FEP was construed to refer to the effect of the changes in the flow properties of faults resulting from fault movement. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: The effects of changes to fault systems 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 2000e). Changes in stresses, regardless of the proximal cause, may result in changes to the hydrologic characteristics of faults, as expressed in the parameter of fracture aperture. The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) in fault zones was examined because several fracture properties (permeability, capillary pressure, and porosity) are functions of fracture aperture (CRWMS M&O 2000e). The results indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the UZ (CRWMS M&O 2000e, Section 7).

Therefore, thermo-mechanical stress effects on the UZ are *Excluded* from the TSPA-SR based on low consequence to dose.

Primary FEP: Changes in Stress (Due to Seismic or Tectonic Effects) Alter Perched Water Zones

FEP Number: 2.2.06.03.00	**Primary 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.
Primary Assigned to: Disruptive Events FEPs, Unsaturated Zone FEPs.	
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose
Number of Secondaries: *1* Screening Decision: *Excluded* from the TSPA-SR	

Geologic Process: Tectonism or Seismicity. The FEP is not process-specific

Potential Consequences: This FEP is concerned with tectonic or seismic activity that alters the rock permeability and affects the formation or persistence of perched-water zones. Changes in stress due to all causes have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Geologic Setting: Yucca Mountain is located in the Southern Great Basin Province, which is in the waning phase of Basin and Range crustal extension. The local tectonic setting is one of block-faulted and eroded mountains with low-to-moderate historical seismicity. The peak phase of tectonism took place 12 to 11.6 Ma.

Discussion: See *Features, Events, and Processes in UZ Flow and Transport* ANL-NBS-MD-000001: CRWMS M&O (2000q, Section 6.7.9) for a more detailed explanation of this FEP.

It seems unlikely that a change in stress could, in itself, adequately seal a zone such that perched water develops. However, the generation of perched water above the repository as a result of tectonic or seismic activity could potentially affect the flow of water to waste emplacement drifts. The potential effect is indirectly included using a model for focused flow in the seepage-model abstraction.

Changes in stress, regardless of the proximal cause (e.g., seismicity, tectonism, faulting, heating) may result in changes to the hydrologic characteristics of fractures, as expressed through the parameter of fracture aperture. The permeability of the matrix, on the other hand, is not expected to be as sensitive to mechanical strain. The effects of changes to fracture systems 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 2000e). The effect of changes in fracture apertures (0.2 times to 10 times the existing fracture apertures) was examined because several fracture properties (permeability, capillary pressure, and porosity) are a function of fracture aperture. The results of the analysis indicate that radionuclide transport in the Yucca Mountain region is relatively insensitive to large variations in the fracture aperture. Because transport properties in the UZ are not significantly affected, changes in the state of stress do not provide a mechanism that could significantly change the dose. Therefore, effects of changes in stress are *Excluded* from the TSPA-SR based on low consequence to dose.

The potential to release perched water as a result of stress changes and fracture openings due to seismic activity, however, is also considered and hypothetically has the potential to result in a relatively sharp "pulse" of radionuclides. The relatively small volume of water *in the fracture domain* below the potential repository, and the radionuclides that could be contained in this water, however, are not expected to cause a significant "pulse" in radionuclide mass flux at the water table. Consequently, this FEP is *Excluded* from the TSPA-SR on the basis of low consequence to dose.

Relation of Elements of Primary Description to Secondary FEPs:

The Secondary FEP description is nearly identical to that of the primary FEP.

References: *Fault Displacement Effects on Transport in the Unsaturated Zone* ANL-NBS-HS-000020 (CRWMS M&O 2000e).

Primary FEP: Changes in Stress (due to Seismic or Tectonic Effects) Alter Perched Water Zones (continued)

Links to FEPs that examine related but distinct effects and consequences
Tectonic activity—large scale (1.2.01.01.00) Fractures (1.2.02.01.00) Faulting (1.2.02.02.00) Igneous activity causes changes to rock properties (1.2.04.02.00) Hydrologic response to igneous activity (1.2.10.02.00) Hydrologic response to seismic activity (1.2.10.01.00) Focusing of unsaturated flow (fingers, weeps) (2.2.07.04.00)
Links to FEPs that examine similar effects and consequences
Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock (2.2.06.01.00) Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults (2.2.06.02.00)

Links to IRSR

Directly Related KTI Subissues:

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Classification and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS3: Fractures
USFIC3: Shallow Infiltration
USFIC4: Deep Percolation

Integrated Subissues / Related Subissues:

ENG1: Degradation of Engineered Barriers / CLST1, CLST6
ENG3: Quantity and Chemistry of Water Contacting the Waste Package and Waste Form / ENFE1, ENFE2, CLST1, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, ENFE1, SDS3
UZ2 Geo: Flow Paths in the UZ / USFIC4, ENFE1, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC5, SDS3

Primary FEP: Changes in Stress (due to seismic, or tectonic effects) Alter Perched Water Zones
Secondary FEP: Perched zones develop as a result of stress changes

FEP Number: 2.2.06.03.01	**Originator FEP Description**: Strain due to stress changes from tectonic and seismic events alter the permeabilities and allow development of perched water zones.
Screening Decision: *Excluded* from the TSPA-SR	**Screening Decision Basis**: Low consequence to dose

Potential Consequences: Changes in stress due to all causes (including tectonic and seismic activity) have a potential to result in strains that affect groundwater flow-and-transport properties, leading to increased or decreased dose. Changes in flow through the drifts have the potential to result in increased degradation of components of the EBS and waste packages, leading to a release of radionuclides.

Discussion: The Secondary and Primary FEP descriptions are almost identical. See discussion for the Primary FEP.