OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

ANALYSIS/MODEL COVER SHEET

1. QA: QA

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COMPLETE ONLY APPLICABLE ITEMS

2. X Analysis — Check all that apply

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

Describe use: This AMR is intended to summarize the decisions, arguments, and disposition of System-Level FEPs, and provide input into the YMP FEP Database

3. ☐ Model — Check all that apply

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

Describe use:

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12. Remarks:

Attachment I is a Glossary, Attachments II, IIA, and IIB address System-Level FEPs. Attachment IIB is done as a hand calculation. Results of hand calculations are provided in the Tables in Attachment IIB. EXCEL was used to prepare graphics for Figures used in Attachment IIB and to verify hand calculations. Attachment III addresses Criticality FEPs.

Input was received from Peter Gottlieb and Peter Swift for Section 6.3

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD
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TABLES

ATTACHMENTS

ACRONYMS AND ABBREVIATIONS

Acronyms

AMR	Analysis/Model Report
AP	Administrative Procedure
CFR	Code of Federal Regulations
CLST	Container Life and Source Term
CRWMS	Civilian Radioactive Waste Management System
CSNF	Commerical Spent Nuclear Fuel
DIRS	Document Input Reference System
DOE	Department of Energy
DSNF	Department of Energy Spent Nuclear Fuel
EBS	Engineered Barrier System
EIS	Environmental Impact Statement
ENFE	Evolution of the Near Field Environment
EPA	Environmental Protection Agency
ESF	Exploratory Studies Facility

ACRONYMS AND ABBREVIATIONS (continued)

FEP	Feature, Event, or Process
FR	Federal Register
ICN	Interim Change Notice
IRSR	Issue Resolution Status Report
ISI	Integrated Subissue
LADS	License Application Design Selection
M&O	Management and Operating Contractor
NAGRA	National Cooperative for the Disposal of Radioactive Waste of Switzerland
NAS	National Academy of Sciences
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
OCRWM	Office of Civilian Radioactive Waste Management
OECD	Organization for Economic Co-operation and Development
PMR	Process Model Report
QAP	Quality Administrative Procedure
QARD	Quality Assurance Requirements and Description
RMEI	Reasonably Maximally Exposed Individual
RT	Radionuclide Transport
SNF	Spent Nuclear Fuel
SZ	Saturated Zone
TSPA	Total System Performance Assessment
TSPAI	Total System Performance Assessment and Integration
TSPA–SR	Total System Performance Assessment-Site Recommendation
UZ	Unsaturated Zone
YAP	Yucca Mountain Administrative Procedure
YMP	Yucca Mountain Project
WIPP	U.S. DOE Waste Isolation Pilot Plant

ACRONYMS AND ABBREVIATIONS (continued)

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
M.y.	million years (duration)
yr	year

1. PURPOSE

The primary purpose of this Analysis/Model Report (AMR) is to identify and document the screening analyses for the features, events, and processes (FEPs) that do not easily fit into the existing Process Model Report (PMR) structure. These FEPs include the 31 FEPs designated as System-Level Primary FEPs and the 22 FEPs designated as Criticality Primary FEPs. A list of these FEPs is provided in Section 1.1. This AMR (ANL-WIS-MD-000019) documents the Screening Decision and Regulatory Basis, Screening Argument, and Total System Performance Assessment (TSPA) Disposition for each of the subject Primary FEPs. This AMR provides screening information and decisions for the TSPA–SR report and provides the same information for incorporation into a project-specific FEPs database. This AMR may also assist reviewers during the licensing-review process.

This scope of this AMR was initially 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). 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 and documented in *Monitored Geologic Repository Project Description Document* TDR-MGR-SE-000004 REV 02 (CRWMS M&O 2000b). These design changes included reorientation of the emplacement drifts to an orientation of azimuth 252/72, removal of backfill from the design, and consideration of repository layout/relocation to accommodate both a 70,000-metric-ton uranium (MTU) and 97,000-MTU design. This AMR addresses evaluations for both the backfill and no-backfill repository designs.

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 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 has been prepared to satisfy the FEP-screening documentation requirements described in the Technical Work Plan entitled *Analyses to Support Screening of System-Level Features, Events, and Processes for the Yucca Mountain Total System Performance Assessment–Site Recommendation, Rev 01.* TDP-WIS-MD-000002 REV 00 (CRWMS M&O 1999c). The current FEPs list for YMP consists of 1,797 entries as described in Section 1.2. The FEPs have been 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 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 System-Level and Criticality FEPs is documented in AMRs prepared by the responsible PMR groups. However, based on the collective judgement of the subject-matter experts and as described in Section 1.2, the System-Level FEPs were best assigned to the TSPA itself rather than to the supporting PMRs. Likewise, Criticality FEPs were not assigned to a specific PMR and were assigned as separate items to the subject-matter experts. The System-Level and Criticality FEPs screening results are included in this document.

In the original FEP assignments, 26 FEPs were originally designated as System-Level FEPs. Five FEPs were subsequently reassigned to the System-Level FEPs report. This AMR addresses the 31 FEPs (26 originally assigned plus 5 reassigned) that have been identified as System-Level FEPs. These FEPs are best dealt with at the system level. They do not fall within other PMRs, they are directly addressed by proposed regulations, guidance documents, or assumptions listed in the proposed regulations, or they are addressed in background information used in development of the proposed regulations. The 31 System-Level Primary FEPs addressed in this AMR were derived from the current version of the *YMP FEP Database* (CRWMS M&O 2000d, Appendix D). The 31 System-Level FEPs addressed in this AMR include:

Table 1. System-Level FEPs

FEP Name	YMP FEPs Database Number
Timescales of Concern	(0.1.02.00.00)
Spatial Domain of Concern	(0.1.03.00.00)
Regulatory Requirements and Exclusions	(0.1.09.00.00)
Model and Data Issues	(0.1.10.00.00)
Records and Markers, Repository	(1.1.05.00.00)
Repository Design	(1.1.07.00.00)
Quality Control	(1.1.08.00.00)
Schedule and Planning	(1.1.09.00.00)
Administrative Control, Repository Site	(1.1.10.00.00)
Monitoring of Repository	(1.1.11.00.00)
Accidents and Unplanned Events During Operation	(1.1.12.01.00)
Retrievability	(1.1.13.00.00)
Metamorphism [1]	(1.2.05.00.00)
Diagenesis [1]	(1.2.08.00.00)
Salt Diapirism and Dissolution [1]	(1.2.09.00.00)

Table 1. System-Level FEPs (continued)

Diapirism [1]	(1.2.09.01.00)
Deliberate Human Intrusion	(1.4.02.01.00)
Inadvertent Human Intrusion	(1.4.02.02.00)
Unintrusive Site Investigation	(1.4.03.00.00)
Drilling Activities (Human Intrusion)	(1.4.04.00.00)
Effects of Drilling Intrusion	(1.4.04.01.00)
Mining and Other Underground Activities (Human Intrusion)	(1.4.05.00.00)
Explosions and Crashes (Human Activities)	(1.4.11.00.00)
Meteorite Impact	(1.5.01.01.00)
Extraterrestrial Events	(1.5.01.02.00)
Changes in the Earth's Magnetic Field	(1.5.03.01.00)
Earth Tides	(1.5.03.02.00)
Salt Creep	(2.2.06.05.00)
Effects of Repository Heat on the Biosphere	(2.3.13.03.00)
Atmospheric Transport of Contaminants [2]	(3.2.10.00.00)
Toxicity of Mined Rock	(3.3.06.01.00)

Notes:
[1] Reassigned to System-Level FEPs from Disruptive Events
[2] Reassigned to System-Level FEPs from Biosphere

This AMR also addresses the 22 FEPs that have been identified as Criticality Primary FEPs. These 22 Primary FEPs represent processes and process interactions internal to the waste package, in the near-field environment (NFE), and in the far-field environment, that have the potential to produce conditions conducive to criticality. The 22 Criticality FEPs addressed in this AMR were derived from the current version of the *YMP FEP Database* (CRWMS M&O 2000d, Appendix D). Earlier versions of the database listed 25 Primary FEPs, but after examination by the subject-matter experts, adjustments were made in the assignments of primary and secondary FEPs, resulting in a total of 22 Criticality Primary FEPs. No Criticality FEPs were deleted from the list; however, three FEPs were reassigned. The 22 Criticality Primary FEPs addressed in this AMR include:

Table 2. Criticality FEPs

FEP Name	YMP FEPs Database Number
Criticality in waste and EBS	(2.1.14.01.00)
Criticality in-situ, nominal configuration, top breach	(2.1.14.02.00)
Criticality in-situ, waste package internal structures degrade faster than waste form, top breach	(2.1.14.03.00)
Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach	(2.1.14.04.00)
Criticality in-situ, waste package internal structures degrade slower than waste form, top breach	(2.1.14.05.00)
Criticality in-situ, waste form degrades in place and swells, top breach	(2.1.14.06.00)
Criticality in-situ, bottom breach allows flow through waste package, fissile material collects at bottom of waste package	(2.1.14.07.00)

Table 2. Criticality FEPs (continued)

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place	(2.1.14.08.00)
Near-field criticality, fissile material deposited in near field pond	(2.1.14.09.00)
Near-field criticality, fissile solution flows into drift low point	(2.1.14.10.00)
Near-field criticality, fissile solution is adsorbed or reduced in invert	(2.1.14.11.00)
Near-field criticality, filtered slurry or colloidal stream collects on invert surface	(2.1.14.12.00)
Near-field criticality associated with colloidal deposits	(2.1.14.13.00)
Out-of-package criticality, fuel/magma mixture	(2.1.14.14.00)
Critical assembly forms away from repository	(2.2.14.01.00)
Far-field criticality, precipitation in organic reducing zone in or near water table	(2.2.14.02.00)
Far-field criticality, sorption on clay/zeolite in TSbv	(2.2.14.03.00)
Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ	(2.2.14.04.00)
Far-field criticality, precipitation in perched water above TSbv	(2.2.14.05.00)
Far-field criticality, precipitation in fractures of TSw rock	(2.2.14.06.00)
Far-field criticality, dryout produces fissile salt in a perched water basin	(2.2.14.07.00)
Far-field criticality associated with colloidal deposits	(2.2.14.08.00)

The development and analyses of the FEPs list is outlined in Section 1.2, the FEPs-screening process is described in Section 1.3, and the origin of the YMP FEPs Database classification and numbering system is discussed in Section 1.4.

1.2 FEPs DEVELOPMENT AND ANALYSES

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 2000d, 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 2000d, 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 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 et al. 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 of layers, headings, and categories. The structure of the NEA FEP database is defined by a total of 150 layers, categories, and headings. The YMP FEP Database uses the same structure as the NEA FEP database (see Section 1.4); however, Barr (1999) identified an additional heading relevant to YMP (the Nuclear Criticality heading in the Geologic Environment category) that was not in the NEA database. Therefore, the YMP FEP Database was modified to include a total of 151 layers, categories, and headings. Each of the layers, categories, and headings is an individual entry in the YMP FEP Database, as are the 1,261 FEPs incorporated from the NEA database. Consequently, the YMP FEP Database, prior to the addition of YMP-specific FEPs, contained a total of 1,412 entries.

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 1988 search of YMP literature 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 81 specific FEP entries and one additional YMP-specific heading entry. Many of these additional FEPs were developed informally during roundtable discussions at the workshops and have no formal documentation other than workshop notes; nevertheless, they 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 2000d, 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. The previously used alphanumeric identifier (called the "NEA category" in the database) has 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 contains 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" resulting from the narrow definition. For efficiency, both FEPs and scenarios have been 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. Definitions for terms used in the FEP descriptions and screenings are provided in the Glossary in Attachment I. The Primary and Secondary FEP descriptions are provided in Attachments II and III. For each FEP discussed in Sections 6.2 and 6.3, the relationships of the Primary FEPs to the Secondary FEPs are shown under the heading of *Treatment of Secondary FEPs.* The relationships of Primary FEPs to Key Technical Issues (KTIs) and Subissues and to Integrated Subissues (see NRC 1999a, b, c, d and 2000) are provided under the heading *IRSR Issues.* The interrelationships of Primary FEPs, including those not addressed in this document, are provided under the heading *Related Primary FEPs.*

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 Primary FEPs as needed.

Prior to and during the FEPs screening process, the Primary and Secondary FEPs were reviewed (1) to verify that the FEPs had been appropriately assigned to the System-Level and Criticality report; (2) to ensure that other FEPs (either previously identified or not identified) were being addressed either in these or other Primary FEPs; and (3) to determine that all Secondary FEPs were appropriately included within the Primary FEP descriptions.

1.3 FEPs SCREENING ANALYSIS AND 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 197 (64 FR 46976). The screening criteria are summarized here and are discussed in more detail in Section 4.2.

- Is the FEP specifically ruled out by the guidance or proposed regulations, or is it contrary to the stated guidance or regulatory assumptions?
- Does the FEP have a probability of occurrence of 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 4.2.2.2, 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. Exclusion of a FEP from the TSPA–SR signifies that the FEP satisfies one or more of the above-listed screening criteria. In that case, the FEP is not modeled in the TSPA–SR.

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 probability weighting in 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, for the purposes of probability weighting in the TSPA, is presumed to have a probability of occurrence during the period of performance of less than 1.0, but greater that the screening criteria of $10^{-4}/10^{4}$year.

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 "By Regulation" 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 197 (64 FR 46976) are relevant to many of the FEPs. FEPs that are contrary to DOE's Interim Guidance, specific proposed regulations, regulatory assumptions, or regulatory intent are excluded from further consideration. Examples include: the explicit exclusion of consideration of all but a stylized scenario to address treatment of human intrusion (Dyer 1999, Section 113(d); 64 FR 8640, §63.113(d)); assumptions about the critical group to be considered in the dose assessment (Dyer 1999, Section 115; 64 FR 8640, §63.115); and the intent that the consideration of "the human intruders" be excluded from the human-intrusion assessment (64 FR 8640, Section XI. Human Intrusion). Regulatory arguments for exclusion are used extensively in the System-Level FEPs screening. This regulatory basis for exclusion is denoted by the phrase "By Regulation" in the discussions of the screening decision and regulatory basis presented in Sections 6.2 and 6.3.

1.3.2 "Low Probability" Exclusion

Probability estimates used in the FEPs screening process are based on a technical analysis by either consideration of bounding conditions or a quantitative analysis, and, in some cases, involve a formalized expert elicitation (such as seismic- and volcanic-hazard probabilities). Probability arguments, in general, include 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, an event is defined 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." For probability considerations, this definition of event involves: (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 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, then the phenomenon is excluded from the TSPA. This AMR does not use the first basis for the FEPs argument.

A second basis for the probability screening is invoked if an event is defined in terms of the behavior (or response) of the repository, rather than solely in terms of the behavior of the independent geologic phenomenon. This distinction is important for FEPs 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 (or response) of the repository is of low probability, regardless of the probability of the various events that may have contributed to it.

For example, the probability of meteorite impact can be defined solely in terms of the probability of any meteorite impact on the surface of the repository, and for very small meteorites, the probability of impact during the repository performance period (10,000 years) begins to approach one. However, it is the behavior of the repository in response to impacts (e.g., exhumation of waste packages, fracturing of rock to the repository depth, or fracturing to a given depth) that is of interest for FEPs screening. The probability of the repository behavior is determined in part by the distribution of meteorite size and composition, the areal dimensions of the waste emplacement area or other areas of interest, the specified depth of interest, and the particular behavior of interest (e.g., exhumation or fracturing). Also, certain criticality conditions are dependent both on a low-probability geologic event and on a low-probability response of the repository system and are, therefore, excluded based on "low probability."

The response of the repository system is typically discussed in terms of the degree of *damage*, *failure*, *breaching*, or *impairment*. For this document, 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 feasible due to a penetration, rupture, or tear in the drip shield.

- *Impairment* is loosely defined as applying to other effects, such as accelerated degradation, accelerated corrosion rates, or stress cracking, which 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: if no damage or impairment of engineered systems occurs, then there is no mechanism for release or accelerated release of radionuclides and, therefore, there is no significant change to dose. For example, the probability of "Changes in the earth's magnetic field" has not been quantified but is not an overly common geologic occurrence. Of more importance to the FEPs screening, however, is that there is no known or projected impact on the repository performance. Consequently, the FEP potentially could be excluded as either based on "low probability" or on "low consequence to dose." The basis for low-consequence-to-dose arguments 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., based on "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. 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, and/or other components of the 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 may be 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 based on "low consequence to dose."

Various means to demonstrate negligible impact include: site-specific data, 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- and seismic-related 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 to contain the information related to the "FEP Screening Decision and Regulatory Basis", "Screening Argument", and "TSPA Disposition" that are provided in Sections 6.2 and 6.3.

The structure of the *YMP FEP Database* follows the NEA classification scheme, which uses a hierarchical structure of layers, categories, and headings. The *YMP FEP Database* (CRWMS M&O 2000d, Appendix D) has 4 layers, 12 categories, and 135 headings. The relationships between these layers, categories, and selected headings are shown below in Table 3

Table 3. 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)

Table 3. YMP FEP Database Structure (continued)

Layers	Categories	Total Number of Headings (and general heading descriptions*)
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 (which for traceability sake, have been retained in the database as the "NEA category"). 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 "Meteorite Impact" is assigned the unique database number of (1.5.01.01.00). This signifies that it is an external factor (1.x.xx.xx.xx), under the category of "other factors" (1.5.xx.xx.xx), is listed under the first heading (1.5.01.xx.xx), and is the first Primary FEP under the heading (1.5.01.01.00). The unique database numbers for the 31 Primary System-Level FEPs and the 22 Criticality FEPs are shown in Tables 1 and 2, respectively (Section 1.1) and are included in the report section headings under Section 6.2 and 6.3, respectively. 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 responsible manager for Performance Assessment Operations 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 1999b) 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. Though 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 activity evaluation remains in effect. Preparation of this analysis did not require the classification of items in accordance with QAP-2-3 *Classification of Permanent Items.* This activity is not a field activity. Therefore, 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) quality-assurance program, using approved procedures initially identified in the development plan entitled *Analyses to Support Screening of System-Level Features, Events, and Processes for the Yucca Mountain Total System Performance Assessment–Site Recommendation Rev 01* TDP-WIS-MD-000002 REV 00 (CRWMS M&O 1999c).

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. With regard to the development plan, the control of electronic management of data was evaluated in accordance with YAP-SV.1Q *Control of the Electronic Management of Data.* This evaluation determined that the current work processes and procedures are adequate for the control of electronic management of information for this activity. Though YAP-SV1.Q has been superceded by AP-SV1.Q, this evaluation remains in effect.

The list of the 31 System-Level Primary FEPs and 22 Criticality Primary FEPs addressed in this AMR was derived from the *YMP FEP Database* REV 00. 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 Information.*

3. COMPUTER SOFTWARE AND MODEL USAGE

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

This AMR was developed using only commercially approved software (Microsoft® *Word 97*) for word processing, which is exempt from qualification requirements in accordance with AP-SI.1Q *Software Management.* There were no additional applications (Routines or Macros) developed using this commercial software. Microsoft® *Excel 97* was used to graphically present the meteorite impact probability data and to provide regression analysis using the graphical interface for adding trendlines, as presented in Attachment IIB.

4. INPUTS

4.1 DATA AND PARAMETERS

The technical information used in this AMR as input has been obtained, where possible, from controlled source documents and references using the appropriate document identifiers or records system accession number.

The nature of the FEP-screening arguments and TSPA dispositions is such that cited data and information are used to support reasoned FEP-screening arguments or TSPA dispositions, rather than being used as direct inputs to computational analysis or models. Consequently, the data cited in the FEP-screening Arguments and TSPA dispositions are largely corroborative or referential 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 dispositions.

Because of its reliance on the supporting AMRs and Calculations, this document and its conclusions may be affected by subsequent changes and revisions to the supporting documents cited in Sections 6.2 and 6.3. The impact of the changes and revisions will be managed in accordance with the provisions of AP-3.10Q, AP-3.15Q, and AP-3.17Q.

4.2 CRITERIA

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

Individual System-Level and Criticality FEPs are related to acceptance criteria presented in KTI Subissues and to Integrated Subissues (ISIs) for subject-specific Issue Resolution Status Reports (IRSRs). Of particular importance are the *Issue Resolution Status Report Key Technical Issue: Total System Performance Assessment and Integration* (TSPAI)(NRC 2000, Subissues 1 and 2); *Issue Resolution Status Report Key Technical Issue: Container Life and Source Term* (CLST) (NRC 1999a, Subissue 5); *Issue Resolution Status Report Key Technical Issue: Evolution of the Near Field Environment* (ENFE) (NRC 1999b, Subissue 5); and *Issue Resolution Status Report Key Technical Issue: Radionuclide Transport* (RT) (NRC 1999c, Subissue 4). The FEPs, in many instances, do not specifically address the stated acceptance criteria in the referenced IRSRs, but the Screening Argument and TSPA Disposition statements provided in Sections 6.2 and 6.3 do cite related AMRs, calculations, or other supporting information that are relevant to, and that address, the stated criteria. The relationship of the FEPs to the Subissues and to ISIs in the cited IRSRs is provided in Sections 6.2 and 6.3.

The FEPs identification and screening is 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 (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.

The FEP-specific criteria for in-package criticality are provided in *Issue Resolution Status Report Key Technical Issue: Container Life and Source Term* (NRC 1999a) under CLST Subissue 5: The Effects of In-Package Criticality on Waste Package and Engineered Barrier Subsystem Performance and are discussed below in Section 4.2.1.5. The FEP-specific criteria for near-field criticality are provided in *Issue Resolution Status Report Key Technical Issue: Evolution of the Near Field Environment* (NRC 1999b) under ENFE Subissue 5: Coupled Thermal-Hydrologic-Chemical Processes Affecting Potential Nuclear Criticality in the Near Field and are discussed below in Section 4.2.1.6. The FEP-specific criteria for far-field criticality are provided in *Issue Resolution Status Report Key Technical Issue: Radionuclide Transport* (NRC 1999c) under RT Subissue 4: Nuclear Criticality in the Far Field, and are discussed below in Section 4.2.1.7. The applicable acceptance criteria pertaining to FEPs evaluation 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, Section 4.1.1.2) 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 satisfy Criterion T1, the FEP-screening process for the System-Level and Criticality FEPs is described in Section 1.3 and Section 6.1 of this document. The relationships of the System-Level and Criticality Primary FEPs to other relevant FEPs are detailed in Sections 6.2 and 6.3 and, thereby, satisfy Criterion T2. The classification of FEPs as primary or secondary is discussed in Section 1.2 of this document and satisfies Criterion T2.

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

The TSPAI (NRC 2000, Section 4.2.1) states that DOE's approach in identifying an initial list of processes and events will be acceptable if the following 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 satisfy Criterion T1, a summary of the approach and methods used to identify the list of process and events is provided in Section 1.2 of this document. 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 2000d).

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

The TSPAI (NRC 2000, Section 4.2.2) states that DOE's classification of processes and events will be acceptable, if the following 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 satisfy Criterion T1 and Criterion T2, the categorization (or classification) of the list of processes and events is discussed in Section 1.2 of this document. The categorization is also addressed through the database organization and FEP numbering as summarized in Section 1.4 of this document. 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 2000d).

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

The TSPAI (NRC 2000, Section 4.2.3) states that DOE's screening of categories of processes and events will be acceptable if the following 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, TSPAI as worded here is unclear, so the language has been omitted .]

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 over 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 satisfy Criteria T1, T3, and T4, the Screening Decision (*Included* or *Excluded*) and Regulatory Basis ("By Regulation," "Low probability," or "Low consequence to dose"), and the Screening Argument and/or TSPA Disposition are discussed for each System-Level or Criticality Primary FEP under Section 6.2 and 6.3 of this document. Similar information for the related Secondary FEPs is also provided.

Criterion T1 allows for screening based on repository design and corresponds to Assumptions 5.2 and 5.3 discussed in Section 5.1 of this document. Accordingly, Criterion T1 is 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 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 satisfied because (1) the probabilities used in the FEPs screening and in the TSPA–SR are cited from supporting documents, or (2) the probability calculations are included in this AMR. In either case, the probability has been shown to be consistent with site data, it is well documented, and it addresses uncertainty.

Criteria T3 and T4 are 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 FEPs 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 arguments is provided for each Primary FEP in Section 6.2 and 6.3.

4.2.1.5 CLST Subissue 5: The Effects of In-Package Criticality on Waste Package and Engineered Barrier Subsystem Performance

The CLST (NRC 1999a) lists seven acceptance criterion pertaining to Criticality: design criteria, scenarios, configurations, probability, analysis, consequence, and risk. Many of the Primary FEPs discussed in Section 6.3, deal with configuration classes and configurations (and are, therefore, germane to resolution of criticality-related subissues), but the acceptance criterion for configuration is not directly related to FEP-screening criteria. However, of particular interest to this AMR are the acceptance criteria stated for scenarios and probability. These are listed (NRC 1999a Section 4.5.1) as Acceptance Criteria (2) and (4), respectively, and are stated as follows:

(2) DOE has identified all the features, events, and processes that may increase the reactivity of the system inside the WP [waste package]. The acceptance criteria provided for the Scenario Analysis subissue in the Total System Performance Assessment and Integration (TSPAI) IRSR must also be considered.

(4) DOE has developed a technically defensible, transparent, and traceable method in assigning probability values to each of the scenario classes, scenarios, configuration classes, and configurations.

Acceptance Criterion (2), is, at least, partially satisfied by this AMR. Tables 2 and 5 of this AMR identify the FEPs that are of interest to criticality, and the FEP Descriptions for both Primary and Secondary FEPs are provided in Attachment III. Section 6.3 addresses each in-package Criticality FEPs (see Sections 6.3.1 through 6.3.8), and includes consideration of the FEPs in terms of the effects on producing conditions favorable to in-package criticality, particularly those related to igneous activity, seismicity, and rockfall events. The Scenario Analysis subissue for the TSPAI is discussed in *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-000001 (CRWMS 2000c, Section 4).

Acceptance Criteria (4) is, at least, partially satisfied by this AMR. The screening arguments for the in-package Criticality FEPs are provided in Section 6.3 (see Sections 6.3.1 through 6.3.8), and the FEPs are consistently excluded based on low probability. The basis for the low-probability argument is provided in the discussion for each of the Criticality Primary FEPs through citations to supporting documents.

4.2.1.6 ENFE Subissue 5: Coupled Thermal-Hydrologic-Chemical Processes Affecting Potential Nuclear Criticality In the Near Field

The ENFE (NRC 1999b, Section 4.5.1) lists acceptance criteria for Subissue 5 under the subheading of "4.5.1 Review Methods and Acceptance Criteria." The acceptance criteria are grouped by various topics. Of particular interest to this AMR are the Integration Acceptance Criteria. Acceptance Criterion (1) is stated as follows:

(1) DOE has considered all the relevant features, events, and processes. The abstracted models adequately incorporated important design features, including criticality safety features; physical phenomena and couplings, including neutron absorbers; and used consistent and appropriate assumptions throughout.

Acceptance Criterion (1) is, at least, partially satisfied by this AMR. Tables 2 and 5 of this AMR identify the FEPs that are of interest to the criticality, and the FEP Descriptions for both Primary and Secondary FEPs are provided in Attachment III. Section 6.3 (see Section 6.3.9 through 6.3.14) addresses each near-field Criticality FEP and includes consideration of the FEPs in terms of the effects on producing conditions favorable to criticality, particularly those related to igneous activity, seismicity, and rockfall events. The basis for the low-probability argument is provided in the discussion for each of the Criticality Primary FEPs through citations to supporting documents.

4.2.1.7 RT Subissue 4: Nuclear Criticality in the Far Field

The RT (NRC 1999c, Section 4.4.1) states that the acceptance criteria for DOE's approach to evaluating and abstracting nuclear criticality in the far field in a TSPA have been removed pending inclusion in a future NRC document that is under development. A review of the previous version of the RT (NRC 1999d, Section 4.4.1) indicated that two acceptance criteria were previously provided. Of particular interest to the FEPs screening was Criterion (1), which stated:

> (1) DOE has determined the probabilities of scenarios that lead to the accumulation of a critical mass of fissile material into a critical configuration within 10,000 years in the farfield using appropriate site characteristics.

Acceptance Criteria (1) is, at least, partially satisfied by this AMR. The screening arguments for the far-field Criticality FEPs are provided in Section 6.3 (see Sections 6.3.15 through 6.3.22), and the FEPs are consistently excluded based on low probability. The basis for the low-probability argument is provided in the discussion for each of the Criticality Primary FEPs through citations to supporting documents.

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 at proposed rule 10 CFR 63 (64 FR 8640). Additional screening criteria are identified by the EPA in 40 CFR 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, which is defined as having less than one chance in 10,000 of occurring in 10,000 years or $10^{-4}/10^{4}$ years, or, as explained in Assumption 5.7, an equivalence of 10^{-8} annual-exceedance probability. The FEP can also be excluded if occurrence of the FEP can be shown to have negligible effect on expected annual dose. There is no quantified definition of "significantly changed" in the guidance or proposed regulations. These technical screening criteria are the same as those discussed in Section 4.2.1.4, for Criteria T1 through T4. Other criteria are specified in the assumption, guidance, or specific criteria in the proposed regulations that address the reference biosphere and the critical group.

The following subsections provide the regulatory citation 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 the criterion for "low consequence to dose" is discussed Section 4.2.2.2. The low-probability and low-consequence-to-dose criteria are used as the technical basis for all of the FEPs screening. 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 FEPs screening, such as considerations of future states of the geologic setting and the distance from the repository to the potential receptor. The standards for analyzing for Human Intrusion are discussed in Section 4.2.2.5.

4.2.2.1 "Low Probability"

The 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, §63.114(d)):

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

The EPA provides essentially the same criterion in proposed 40 CFR 197 (64 FR 46976, §197.40):

> 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, as explained in Assumption 5.7, is equivalent to a 10^{-8} annual-exceedance probability. The use of the low-probability criterion for FEP screening is described in Section 1.3.2 of this document, which notes that low probability is considered on two bases: 1) the probability of a phenomenon (e.g., meteorite impact), and 2) the probability of a specific behavior of the repository in response to the phenomenon (e.g., meteorite impact exhumes waste).

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 the NRC's proposed rule 10 CFR 63 (64 FR 8640, §63.114(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 (64 FR 46976, §197.40):

> . . . 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 phrases "be significantly changed" and "not be changed significantly" are undefined in the DOE's Interim Guidance, and in the NRC's and in the EPA's proposed regulations. These phrases 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 FEPs screening is described in Section 1.3.3 of this document, which notes that low consequence to dose is used if it is demonstrated that there is no or a negligible 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 the EPA's proposed regulations specify conditions and characteristics (which in effect serve as screening criteria) pertinent to screening many of the System-Level and Criticality FEPs. Particularly germane are explicit conditions and characteristics regarding the reference biosphere and the geologic setting.

Conditions and characteristics pertaining to the reference biosphere are presented in DOE's Interim Guidance (Dyer 1999, 115(a)(1-2) and 114(k)) and at proposed rule 10 CFR 63 (64 FR 8640, §63.115 (a)(1-3)).

> (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.
>
> (2) Biosphere pathways shall be consistent with arid or semi-arid conditions.
>
> (3) Climate evolution shall be consistent with the geologic record of natural climate change in the region surrounding the Yucca Mountain site.

The EPA has specified equivalent conditions at proposed rule 40 CFR 197 (64 FR 46976, §197.15). These conditions can be summarized as follows:

> The DOE should not attempt to project changes to society, human biology, or increases or decreases to human knowledge. ...DOE must assume that all of those factors remain constant as they are at the time of license submission to NRC.

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, §63.115(a)(4)) state that:

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

The EPA has specified a similar condition regarding changes that will occur in the next 10,000 years at proposed rule 40 CFR 197 (64 FR 46976, §197.15). 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. Existing features, such as faults, fracture systems, and rock properties, have been included in the geologic framework and in the UZ and SZ flow models, and behaviors of igneous events have been included in the models and analyses used as a basis for FEPs screening. As a result, FEP-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). Some process (e.g., metamorphism) 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) for the processes to result in effects that would significantly affect dose.

These criteria also specify that no attempt should be made to project changes to society, human biology, or increase or decrease to human knowledge. This particularly applies to FEPs dealing with the possibility of human intrusion.

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, §63.115(b)).

> 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) (64 FR 8640, §63.115(b)(1)). *[Note: The wording varies slightly from that provided in Dyer Section 115(b)(1)]*

The EPA-specified assumptions are provided in proposed 40 CFR 197 (64 FR 46976, §197.21(a-c)) 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 System-Level 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 46976), 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 System-Level FEPs.

The characteristics of the critical group to be used in exposure calculations are set by the NRC at proposed rule 10 CFR 63 (64 FR 8640, §63.115(b)) and by the EPA at proposed rule 40 CFR 197 (64 FR 46976, §197.21). Societal and physiological changes, and changes in human knowledge through time are excluded from consideration by both the proposed NRC and proposed EPA regulations.

> . . . Changes over time in the behaviors and characteristics of the critical group including, but not necessarily limited to, land use, lifestyle, diet, human physiology, or metabolics; shall not be considered (64 FR 8640, §63.115(b)(2)).
>
> The DOE should not attempt to project changes to society, human biology, or increases or decreases to human knowledge. ...DOE must assume that all of those factors remain constant as they are at the time of license submission to NRC. (64 FR 46976, §197.15).

Characteristics of the critical group are provided at proposed rule 10 CFR 63 (64 FR 8640, §63.115(b)(1 - 5)):

> (1) 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.)
>
> (2) The behaviors and characteristics of the farming community shall be consistent with current conditions of the region surrounding the Yucca Mountain site.
>
> (3) The critical group resides within a farming community consisting of approximately 100 individuals, and exhibits behaviors and characteristics that will result in the highest expected annual doses.
>
> (4) The behaviors and characteristics of the average member of the critical group shall be based on the mean value of the critical group's variability range . . . .
>
> (5) The average member of the critical group shall be an adult . . . .

The EPA-specified assumptions regarding critical group characteristics are provided at proposed rule 40 CFR 197 (64 FR 46976, §197.21(a - c)) and describe the RMEI. These characteristics are similar to those that NRC describes for the critical group. This hypothetical individual

> (a) . . . lives within one-half kilometer of the junction of U.S. Route 95 and Nevada State Route 373 . . .
>
> (b) Has a diet and living style representative of the people who are now residing in the Town of Amargosa Valley, Nevada. The DOE must use the most accurate projections

> which might be based upon surveys of the people residing in the Town of Amargosa Valley, Nevada to determine their current diets and living styles and use the mean values in the assessments . . .
>
> (c) Drinks 2 liters of water per day from wells drilled into the ground water at the location where the RMEI lives.

The NRC and EPA assumptions regarding characteristics are very similar, although there is a significant difference between the approach of using a "critical group" and the RMEI concept. The difference lies in the conceptual approach to calculating doses and is addressed in the AMRs dealing with the exposure and dose calculations.

4.2.2.5 Human Intrusion

The use of both active and passive institutional controls (such as markers and an information repository) will reduce the potential for human activity. However, it is not possible to make scientifically sound forecasts of the long-term reliability of such controls. Accordingly, the NRC specifies the circumstances of human intrusion at proposed rule 10 CFR 63 (64 FR 8640, §63.113(d)):

> . . . it shall be assumed that the human intrusion occurs at 100 years after permanent closure and takes the form of a drilling event that results in a single, nearly vertical borehole that penetrates a waste package, extends to the saturated zone, and is not adequately sealed.

In the preamble discussions for proposed rule 10 CFR 63 (64 FR 8640, Section XI. Human Intrusion) the NRC also directs that hazards to the intruders themselves (drillers, miners, etc.), or to the public, from material brought to the surface by the assumed intrusion should not be included in the analysis.

The EPA specifies the circumstances of human intrusion at proposed rule 40 CFR 197 (64 FR 46976, §197.26 (a–f)). The EPA-assumed scenario is more specific than the scenario assumed by the NRC. In particular, the EPA specifies that:

> (a) There is a single human intrusion as a result of exploratory drilling for ground water;
>
> (b) The intruders drill a borehole directly through a degraded waste container into the uppermost aquifer underlying the Yucca Mountain repository;
>
> (c) The drillers use the common techniques and practices that are currently employed in the region surrounding Yucca Mountain;
>
> (d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole;

(e) Only releases of radionuclides that occur as a result of the intrusion and that are transported through the resulting borehole to the saturated zone are projected;

(f) No releases are included which are caused by unlikely natural processes and events.

EPA's specification for the timing of the human intrusion is dependent on whether Alternative 1 or Alternative 2 as described at proposed rule 40 CFR §197.25 (64 FR 46976) is selected. If Alternative 1 is selected, then the timing is specified at proposed rule 40 CFR §197.26(g) (64 FR 46976):

(g) The intrusion occurs at a time or within a range of time determined by NRC . . . based upon:

(1) The earliest time that current drilling techniques could lead to waste package penetration without recognition by the drillers;

(2) The time it would take for a small percentage of waste packages to fail but before significant migration of radionuclides has occurred; and

(3) Intrusion would not occur during the period of active institutional control .

If Alternative 2 is selected, then the timing is specified at proposed rule 40 CFR §197.25 (64 FR 46976) as "the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion (see 64 FR 46976, §197.26) could occur without recognition by the drillers."

4.3 CODES AND STANDARDS

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

5. ASSUMPTIONS

The following section addresses assumptions used in the FEPs screening for the System-Level FEPs (Section 5.1) and for the Criticality FEPs (Section 5.2)

5.1 ASSUMPTIONS FOR SYSTEM-LEVEL FEPs

There are seven general assumptions used in screening of the System-Level FEPs.

Assumption 5.1. As directed by DOE's Interim Guidance (Dyer 1999, Section 114(l)) and at proposed rule 10 CFR 63 (64 FR 8640, §63.115(a)(4)), "evolution of the geologic setting consistent with present knowledge of natural processes" is assumed.

Justification: This assumption is justified because it is required by the guidance and screening criteria. Any discernible impacts from past events on the site setting are presumably reflected in the present knowledge of natural processes that form the basis of the TSPA. If the subject FEP phenomena are not reflected in the data used to described past settings (such as geologic and climatological settings that are based on >10,000 year timescales), then they are either of "low consequence to dose" or "low probability" and can be excluded from consideration.

Use: This assumption is used throughout. It is particularly germane to FEPs related to processes or phenomena that, speculatively, could affect future states of the system. These include FEPs such as "Extraterrestrial events" (1.5.01.02.00) (Section 6.2.25), "Earth tides" (1.5.03.02.00) (Section 6.2.27), "Salt Creep" (2.2.06.05.00) (Section 6.2.28). For many of these FEPs, the occurrences of the phenomena are known. However, the effects of the phenomena may be unknown (e.g., effects of a supernova), or the form of the coupling process is unknown (e.g., "Changes in the earth's magnetic field"), or the phenomena have been shown to have no impact or insignificant impact (e.g., "Earth tides").

Assumption 5.2: Design parameters can be used to justify an *exclusion* from the TSPA-SR 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, an event is defined 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 decreased 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 that eliminates or alleviates the interaction is instituted, then the FEP Screening Decision can be determined on that basis.

This assumption is justified because (1) FEPs can be defined temporally, spatially, and in magnitude; (2) the phenomena and effect of the interaction can be quantified (or at least bounded) and, therefore, incorporated into the design; (3) the implementation of the design and changes to the design are subject to a performance-confirmation process; and (4) the "as-built" design can be verified (see Assumption 5.3). Additionally, the TSPAI (NRC 2000, Subissue 2 Acceptance Criterion: Screening of Processes and Events, Criterion T1: see Section 4.2.1.4 of this document) allows for screening based on repository design.

Use: A direct application of this assumption occurs in "Meteorite impact" (Section 6.2.24). The definition of the probability for damage from a meteorite impact is dependent on the depth and areal extent of the repository. A shallower repository could theoretically be affected by a smaller meteorite crater, which occurs more frequently than a larger crater. Similarly, a larger repository area also would increase the probability of a crater occurring over the repository.

Assumption 5.3: It is assumed that the repository will be constructed, operated, and closed according to the design used as the basis for the FEPs 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 include 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 4.2.1.4 of this document) allows for screening based on repository design.

This assumption is further justified based on the conditions specified at proposed rule 10 CFR §63.73(a) (64 FR 8640). This guidance specifies that "DOE shall promptly notify the NRC of each deficiency found in the characteristics of the Yucca Mountain site, and design and construction of the geologic repository operations area that, were it to remain uncorrected, could: 1) be a substantial safety hazard, 2) represent a significant deviation from the design criteria and design bases stated in the application, or 3) represent a deviation from the conditions stated in the terms of a construction authorization or the license, including license specifications." Furthermore, the existing guidance specifies that a performance confirmation program (64 FR 8640, Subpart F) be instituted. Changes from baseline conditions and design must be reported to the NRC as noted at proposed rule 10 CFR §63.132(b and d) (64 FR 8640), which pertains to significant differences between measurements and observations from subsurface monitoring and the original design bases and assumptions.

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. This assumption is needed because a change in the design requires a reevaluation of the Screening Decision for FEPs that are dependent on design requirements.

As an example, this AMR was originally scoped based on consideration of a repository design with backfill, based on *License Application Design Selection Report* (CRWMS M&O 1999a, EDA II, p. 0.12 to 0.22 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 were noted and documented in *Monitored Geologic Repository Project Description Document* TDR-MGR-SE-000004 REV 02 (CRWMS M&O 2000b). The design changes included reorientation of the emplacement drifts to an orientation of azimuth 252/72, inclusion of a drip shield, deletion of the backfill, and consideration of 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 FEPs screening and are presented in this document.

Use: This assumption is used for FEPs related to construction and operational practices including: "Model and data issues" (0.1.10.00.00), "Repository design" (1.1.07.00.00) (Section 6.2.6), "Quality control" (1.1.08.00.00) (Section 6.2.7), "Schedule and planning" (1.1.09.00.00) (Section 6.2.8), "Monitoring of repository" (1.1.11.00.00) (Section 6.2.10), and "Accidents and unplanned events during operation" (1.1.12.01.00) (Section 6.2.11). It also affects "Meteorite impact" (1.5.01.01.00) (Section 6.2.24) since the definition of the probability for damage from a meteorite impact is dependent on the depth and areal extent of the repository.

Assumption 5.4 The assumed timing of the human intrusion at 100 years (proposed rule 10 CFR 63: 64 FR 8640, §63.113(d)) includes two unstated suppositions: 1) That, for the first 100 years after closure, active and/or passive controls are sufficient to effectively prevent intrusion, and 2) That, after the first 100 years, records and markers are lost, ignored, or ineffective in preventing the intrusion.

Justification: This assumption is intrinsic in the specification that an intrusion occurs and the specification of the intrusion at a specified time.

Use: The assumption is used for FEPs related to "Records and markers, repository" (1.1.05.00.00) (Section 6.2.5), "Administrative control, repository site" (1.1.10.00.00) (Section 6.2.9), "Deliberate human intrusion" (1.4.02.01.00) (Section 6.2.17), and "Inadvertent human intrusion" (1.4.02.02.00) (Section 6.2.18).

Assumption 5.5. The following eight specific assumptions are justified from literature on meteoroid flux and impact cratering as noted below. These assumptions are used for the meteorite impact calculations summarized in Section 6.2.24, and are used throughout Attachment IIB.

Assumptions 5.5.1. The frequency of cratering impacts is presumed to be bounded on the lower end by the time distribution of craters observed on earth (since not all craters are known or observed, the frequency may be higher, and thus this is a lower bound) and on the upper end by the total flux of meteor material into the earth's atmosphere less atmospheric shielding effects.

Justification: The assumed distributions are justified based on peer-reviewed journal articles by Grieve (1987 and 1995) for the earth impact records Accordingly, it is assumed that the number of impact craters larger than a crater diameter D, produced per year per square km is proportional to the apparent crater diameter to the –1.8 power (Grieve 1987, p. 257 and Figure 8). Grieve (1995, p. 196) fixes the frequency for D = 20 km at $(5.5 \pm 2.7) \times 10^{-15}/km^2/yr$. The assumed data for the total flux of materials is from Ceplecha (1992, p. 364 and 1994, p. Figure 2), and for atmospheric shielding effects by Hills and Goda (1993).

Use: This assumption is used for the meteorite impact calculations summarized in Section 6.2.24, and is used throughout Attachment IIB.

Assumption 5.5.2. For the meteorite impact calculations, assumed densities are 8 g/cm^3 for metallic meteoroids, 3.7 g/cm^3 for stony material, and 1.1 g/cm^3 for carbonaceous /cometary materials.

Justification: These values are justified based on data reported in Chapman and Morrison, (1994, p. 34) and Ceplecha (1994, p. 967, and Table 1 and 3), and are upper bounding limits for expected densities for the various types of materials.

Use: This assumption is used for the meteorite impact calculations summarized in Section 6.2.24, and is used throughout Attachment IIB.

Assumption 5.5.3. Initial entry velocities are assumed to be at 15 and 20 km/sec, regardless of the meteorite composition or size.

Justification: These assumed velocities are justified because 1) Literature on velocity of known meteoroids and comets indicated velocities ranging from 12.9 km/sec (Chyba 1993, Table 1a) to over 80 km/sec (Marsden and Steel 1994, p. 233-236); and 2) Lower initial velocities tend to result in larger crater diameters (Hills and Goda 1993, p. 1140). Therefore, use of velocities at the lower end of the range of values is a conservative bounding assumption since it tends to result in overstatement of crater diameters.

Use: This assumption is used for the meteorite impact calculations summarized in Section 6.2.24, and is used throughout Attachment IIB.

Assumption 5.5.4. Initial entry is at zenith angle zero for all meteoroids.

Justification: This is a conservative upper bounding assumption. Objects entering at nonzero zenith angles have more kinetic energy absorbed in the atmosphere (Hills and Goda, 1998) and would result in no or smaller crater diameters. This is also an upper bounding assumption because all material entering the atmosphere is considered as potentially impacting the earth's surface regardless of the entry angle. This assumption is needed because there are no data available relating flux and angle of entry.

Use: This assumption is used for the meteorite impact calculations summarized in Section 6.2.24, and is used throughout Attachment IIB.

Assumption 5.5.5. The frequency of iron impactors is assumed to be 3.5 percent of the total flux. Down to an initial meteor mass of approximately 10^8 kg (radius of 18.6 m for stony and 27.9 m for carbonaceous), the remaining flux was divided between stony and carbonaceous material. For initial meteor masses below 10^8 and down to 10^{-1} kg (minimum radius of 0.02 m for stony material and 0.03 m for carbonaceous material), the stony material is presumed to constitute between 2 to 18 percent of the flux, depending on initial meteor radii, and the rest is attributable to carbonaceous material.

Justification: The justification for these assumptions is based on the available literature. Reported values in the literature for iron impactors range from 1 to 6 percent (Chyba 1993, p. 703). Hills and Goda (1998 p. 225) quote Shoemaker as verbally providing a value for the frequency of iron impactors of a given size of 3.5

percent of that of stones. Ceplecha (1992, p. 361) states that bodies in the mass range of 10^{12} and 10^{15} kg are mostly stony or carbonaceous bodies, and, in the range of 10^4 to 10^7 kg, they are mostly inactive comets. Ceplecha (1994, Figure 2) also provides a plot of the percent of stony bodies in this size range; the percentages vary from 2 percent at the 10 m diameter size to approximately 18 percent at the 0.1 m diameter.

Use: This assumption is used for the meteorite impact calculations summarized in Section 6.2.24, and is used throughout Attachment IIB.

Assumption 5.5.6. The repository is assumed to be 250 m below ground surface, and the maximum footprint is assumed to be no larger than 8.6 km by 1.3 km. The area of the repository below the Paintbrush outcrop area above the repository is assumed to be 1.1 km by 0.1 km.

Justification: The area and depth of the repository is based on design data provided in CRWMS M&O (2000a and 2000b). This is a conservative bounding assumption since it uses the shallowest depth of the repository and the largest areal footprint. The area of the repository lying below the Paintbrush outcrop area is based on DOE (1998, Figure 2.8).

Use: This assumption is used for the meteorite impact calculations summarized in Section 6.2.24, and is used throughout Attachment IIB.

Assumption 5.5.7. For simple craters, the depth of exhumation may range from 10 to 30 percent of the crater surface diameter.

Justification: This is a bounding assumption. The full range of values from 10 to 30 percent is evaluated. A maximum value of 30 percent is used in the analysis and is based on cratering dimensions provided in Wuschke et al. (1995, p. 3), Dence et al. (1977, p. 250), and Grieve (1987, p. 248). A value of 30 percent of the diameter represents the maximum depth of exhumation for a given cratering event.

Use: This assumption is used for the meteorite impact calculations summarized in Section 6.2.24, and is used throughout Attachment IIB.

Assumption 5.5.8. For simple craters, the depth of fracturing may range from 0.36 of the crater diameter (based on Dence et al. 1977, p. 261) to as much as 0.76 of the crater diameter (Wuschke et al. 1995, p.3).

Justification: This assumption is justified as a bounding assumption because the maximum and minimum values found in the literature are considered. Additionally this is a bounding assumption because the depth of fracturing reported in the literature is based on rock properties that are less favorable than those of the welded tuff present at Yucca Mountain. A more detailed explanation follows.

Wuschke et al. (1995, p.3) indicate that the depth of fracture in plutonic rock for simple craters could be as high as 0.76 of the crater diameter. The lower limit of fracturing values is based on the Hugoniot Elastic Limit (4.5 gigapascals (GPa), from Melosh 1989, p. 35) for granodiorite (a very low porosity rock).

At Yucca Mountain, however, the rock above and around the repository is layered welded and non-welded tuff, deposited in tilted strata. These tuffs are porous, and their response to shock depends, in part, on their degree of saturation (relative water content). Consequently, a more rapid attenuation of pressure will occur in the Yucca Mountain tuffs than in the plutonic rock or granodiorite used to define the upper and lower limits for fracture propagation. Therefore, fracture depth, which is dependent on shock attenuation, will consequently be shallower at Yucca Mountain than in the granodiorite or plutonic rock for a given cratering event. The importance of the Hugoniot Elastic Limit in determining the fracture depth follows.

The results of the Piledriver nuclear tests used by Dence et al. (1977, p.261) serve as an upper bounding analogue case for evaluating depth of fracturing from meteorite impact at Yucca Mountain. From the Piledriver test, it appears that fracturing was initiated when the shock wave pressure was reduced to 4.5 GPa (the Hugoniot Elastic Limit for granodiorite, from Melosh, 1989, p. 35). Fracturing ceased at depths corresponding to pressures of about 2 GPa, where the rock responds elastically (i.e., without permanent deformation or fracturing) (Dence et al. 1977, p. 261).

In the attenuation models, Dence et al. (1977, p. 261) relate pressure to the radius of the affected region by:

$$P = a\,R^{-k}.$$

The ratio of the pressures at 4.5 GPa and 2 GPa is, therefore, also the ratio of the powers of the respective radii, that is:

$$P_{4.5\,GPa}/P_{2\,GPa} = [R_{2\,GPa}/R_{4.5\,GPa}]^{k}, \quad \text{or}$$

$$R_{2\,GPa} = R_{4.5\,GPa}\,(P_{4.5\,GPa}/P_{2.\,GPa})^{1/k}$$

Since the radius for the onset of fracturing (at 4.5 GPa) is also the true crater depth (or exhumation depth), the radius for 2 GPa becomes

$$R_{2\,GPa} = 0.3D\,(4.5\,/\,2.)^{1/k}\,.$$

The k values (2, 3, and 4.5) for the models are based on fits to the data from the Brent astrobleme and the Piledriver test (Dence et al. 1977, p. 261). Insertion of the values for k provides a range in the relationship of fracture depth to crater diameter of R = 0.45D to R = 0.36D.

Wuschke et al. (1995, p.3) also discuss factors for complex cratering, but the maximum crater diameter of interest (i.e., 2,500 m or 2.5 km) for this analysis falls below the complex-cratering threshold diameter of 4 km in crystalline rock (Grieve 1987, p. 248). The threshold diameter of complex cratering is, however, dependent on the individual host-rock properties.

Consequently, a reasonable lower bound for the fracture depth would be a factor of 0.36. A value of 0.5 (or slightly greater than the 0.45 from Dence et al. (1977, p. 262-264) overestimates the depth of penetration by fractures and, thereby, provides a reasonable upper bound. However, a factor of 0.76 is also evaluated to ensure that the analysis is truly bounding.

Use: This assumption is used for the meteorite impact calculations summarized in Section 6.2.24, and is used throughout Attachment IIB.

Assumption 5.5.9. The vertical extent of effects (e.g., exhumation or fracturing) is represented as a cylinder. The diameter of the cylinder corresponds to the crater diameter, and the depth corresponds to depth of interest derived from the crater diameter, as developed in Assumptions 5.5.7 and 5.5.8.

Justification: This is a conservative bounding assumption. In reality, the effects are more likely spherical in nature (inferred from Wuschke et al. 1995, Figure 1) If a spherical zone is used, the depth of the effect becomes shallower with distance from the centerline of the crater. Consequently, the volume of material affected by meteorites impacting outside the boundary of the repository (i.e., with the centerline of the crater outside the repository but with crater diameters overlapping the boundary of the repository) would be smaller, and located in shallower geologic units. By assuming a cylindrical zone, the maximum depth of the effect (exhumation or fracturing) is applied throughout the area below the crater diameter and, thereby, conservatively considers a larger volume of the material overlying the repository.

Use: This assumption is used for the meteorite impact calculations summarized in Section 6.2.24, and is used throughout Attachment IIB.

Assumption 5.6 Each waste package contains 0.234 to 0.673 Ci of gaseous C-14 . These are bounding assumptions with regard to the C-14 content in the waste packages.

Justification: This assumption is justified based on values used for atmospheric calculations provided by DOE (1999, Section 5.5) and by the EPA (1999, Section 9.2).

Use: This assumption is used in Section 6.2.30.

Assumption 5.7: For postclosure FEPs screening, 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 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. However, due to the time-dependency of radioactive decay, this assumption may not be applicable to probability values for select criticality processes, and should not be assumed unless specifically stated in the individual FEP discussion.

Use: This assumption is used for the FEP "Meteorite impact" (1.5.01.01.00), discussed in Section 6.2.24, and for all the Criticality FEPs addressed in Sections 6.3.1 through 6.3.22, excluding Section 6.3.14.

5.2 ASSUMPTIONS FOR CRITICALITY FEPs

There are no criticality-specific assumptions for this AMR. Assumptions relating to analysis of criticality-related conditions are provided in the cited references for each specific FEP-screening argument.

Assumption 5.7, as stated and justified above, is also applicable to the Criticality FEPs and is used in Sections 6.3.1 through 6.3.22, excluding Section 6.3.14.

6. ANALYSES

This section documents the Screening Decision and Regulatory Basis, Screening Argument, and TSPA Disposition for each of the 31 System-Level Primary FEPs and each of the 22 Criticality Primary FEPs. The following paragraphs discuss the appropriateness and importance of the analyses. Section 6.1 discusses alternative approaches to the FEPs screening, and Sections 6.2 and 6.3 provide the documentation for the individual System-Level and Criticality Primary FEPs.

The FEPs analyses presented in Section 6.2 and 6.3 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 Sections 6.2 and 6.3, and individual FEP subsections).

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 Sections 6.2 and 6.3. The list of processes and events is provided in Section 1.2 of this document. Additional detail regarding identification is provided in the CRWMS M&O (2000d). 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 Sections 6.2 and 6.3 for each of the subject Primary FEPs. The FEP-screening process is described in Section 1.3 of this document. In Sections 6.2 and 6.3 and the individual FEP subsections, the Screening Decision and Regulatory Basis, the Screening Argument, and the TSPA Disposition are discussed for each Primary FEP. Similar information for the related Secondary FEPs is also provided. Where probability arguments are used, the basis for the probability is stated and a reference is cited. Where a low-consequence-to-dose argument is used, the basis for exclusion is 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 63 (64 FR 8640) and by the EPA in 40 CFR 197 (64 FR 46976). The criteria are used to determine whether 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 4.2.2.4), the screening argument includes the regulatory reference and a short discussion of the applicability of the standard.

- 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 basis of the exclusion ("low probability" (Section 4.2.2.1), or "low consequence to dose" (Section 4.2.2.2)) and provides a discussion of the 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 Primary FEP in Sections 6.2 and 6.3 describes how the FEP has been incorporated into the process models or the TSPA–SR abstraction.

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 Data" (AP-3.15Q, Attachment 6), these FEP-screening analyses are 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 assessment." 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 Data."

Section 6.1 addresses alternative approaches for FEP classification and screening. The FEPs screening and analysis for System-Level FEPs is presented in Section 6.2. The FEPs screening and analysis for the Criticality FEPs is presented in Section 6.3. The classification and description of Primary FEPs strive to capture the essence of all the Secondary FEPs that are aggregated into the Primary FEPs. Arguments for Secondary FEP-screening decisions are embedded in the discussion of the Primary FEPs below, as described in Section 1.3. The screening decisions for Secondary FEPs are also provided in Table 4 and Table 5 of Section 7 of this document. Secondary FEP descriptions can be obtained from the *YMP FEP Database* (CRWMS M&O 2000d, Appendix D) and are provided in Attachment II and III.

Because this AMR deals with System-Level and Criticality FEPs, the attachments are numbered to reflect the nature of the subject matter. Attachment I is a general glossary of terms that are used throughout this AMR. Attachments II, IIA, and IIB address System-Level FEPs: Attachment II contains the Primary and Secondary FEP descriptions for the System-Level FEPs, Attachment IIA is an expanded discussion on diagenesis, and Attachment IIB is an expanded discussion on meteorite impacts. Attachment III contains the Primary and Secondary FEP descriptions for the Criticality FEPs.

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

The approach used to identify, analyze, and screen the FEPs (as described in Sections 1.2 and 1.3) is also considered. Alternative classification of FEPs as Primary or Secondary FEPs is possible in an almost infinite range of combinations. Classification into Primary and Secondary FEPs is based primarily on redundancy and on subject matter. Alternative classification of the FEPs is 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 the probabilities and consequence-to-dose used as a basis for screening are discussed in Sections 6.2 and 6.3 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 probability arguments for low-consequence-to-dose events or complex, consequence models for low-probability events. For example, there is no need to develop detailed models of the response of waste packages to meteorite impact if it is shown that meteorite impacts have a probability below the criteria threshold.

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

Alternative interpretations of data as they pertain directly to the FEPs screening are provided in the Supplemental Discussion or Screening Arguments 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 SYSTEM-LEVEL FEPs SCREENING AND ANALYSES

This section addresses the 31 FEPs that have been identified as System-Level Primary FEPs. These FEPs are best dealt with at the system level. They do not fall within other PMRs, and they are directly addressed by regulation, by conditions and characteristics listed in the regulation, or by background information used in development of the regulations. Attachments pertaining specifically to System Level FEPs include Attachments II, IIA, and IIB. Attachment II provides descriptions for the Primary and Secondary FEPs, Attachment IIA is an expanded discussion of diagenesis-related FEPs, and Attachment IIB is an expanded discussion of meteorite-related FEPs

6.2.1 Timescales of Concern (0.1.02.00.00)

FEP Description: This FEP describes the timescale of concern over which the disposal system presents a significant health or environmental hazard.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion

Screening Argument: "Timescales of concern" is *Included* in the TSPA–SR as described under the TSPA Disposition.

TSPA Disposition: "Timescales of concern" is *Included* in the TSPA–SR by assuming a 10,000-year period as the time basis for the performance assessment, as specified by the EPA and the NRC.

Supplemental Discussion: The timescale of concern has been set by the EPA at proposed rule 40 CFR §197.13 (64 FR 46976), which states that ". . . NRC will determine compliance based upon . . . the highest results of DOE's performance assessments projecting the performance of the Yucca Mountain repository for 10,000 years after disposal." Additionally, proposed rule 40 CFR §197.15 (64 FR 46976) specifies that the "...DOE must vary factors related to geology, hydrology, and climate...over the next 10,000 years." The 10,000-year timescale is also specified at proposed rule 40 CFR §197.20 (64 FR 46976) as the period for the performance assessment. A 10,000-year period is also specified at proposed rule 40 CFR §197.25 and §197.35 (64 FR 46976). A 10,000-year timescale is also consistent with the criteria established for "low probability" at proposed rule 10 CFR 63 (64 FR 8640, §63.114(d)) and proposed rule 40 CFR197 (64 FR 46976, §197.40)

At proposed rule 40 CFR §197.30 (64 FR 46976), EPA is also proposing that as part of the performance assessment DOE provide peak dose information after 10,000 years following disposal. However, EPA has also specifically stated that no regulatory standard applies to the results of this analysis, and that the results are not to be used for determining compliance with proposed rule 40 CFR §197.20 (64 FR 46976).

Related PMRs, AMRs, and Calculations: *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-00001 REV 00 (CRWMS M&O 2000c)

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

<u>Integrated Subissues/Related Subissues</u>

ENG1 Eng: Degradation of Engineered Barriers /TEF2, CLST1, CLST2, RDTME3
ENG2 Eng: Mechanical Disruption of Engineered Barriers / CLST1, CLST2, CLST5, SDS2, SD4
ENG4 Eng: Radionuclide Release Rates and Solubility Limits / ENFE4, CLST3, CLST4, CLST5
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC1, USFIC3, USFIC4, TEF2, SDS2, RDTME3
UZ3 Geo: Radionuclide Transport in UZ / USFIC4, USFIC6, ENFE4
SZ2 Geo: Radionuclide Transport in SZ / USFIC5, USFIC6
Dose1 Bio: Dilution of Radionuclides in Groundwater / USFIC5,

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Juvenile and early failure of waste containers and drip shields (2.1.03.08.00)
Container failure (long term) (2.1.03.12.00)
Radioactive decay and ingrowth (3.1.01.01.00

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Regulatory requirements and exclusions (0.1.09.00.00)
Model and data issues (0.1.10.00.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.2.2 Spatial Domain of Concern (0.1.03.00.00)

FEP Description: This FEP describes the spatial domain of concern over which the disposal system may present a significant health or environmental hazard.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion

Screening Argument: "Spatial domain of concern" is *Included* in the TSPA–SR as described under the TSPA Disposition.

TSPA Disposition: "Spatial domain of concern" is *Included* in the TSPA–SR by specifying the spatial boundary conditions for the models and by selecting the individual locations for calculation of exposure and dose.

The "Spatial domain of concern" for the TSPA is an aggregate of the areas defined at proposed rule 10 CFR 63 (64 FR 8640, §63.2 – Geologic Repository, Underground Facility, Site, Geologic Setting), by the location of the Critical Group specified at proposed rule 10 CFR §63.115(b)(1) (64 FR 8640), and of the RMEI at proposed rule 40 CFR §197.21(a) (64 FR 46976). It specifies the area to be used for identifying and selecting a representative volume of groundwater consistent with the intent stated at proposed rule 40 CFR §197.36 (64 FR 46976).

The point of exposure to be evaluated in the performance assessment has been identified by EPA and NRC as near Lathrop Wells (or specifically within 1/2 kilometer of the junction of U.S. Route 95 and Nevada State Route 373). This equates to a distance of approximately 20 km south of the proposed repository.

Supplemental Discussion: The spatial domain considered in the TSPA–SR varies according to the phenomenon being considered. For instance, the spatial domain of concern for a regional groundwater-flow model is bounded on a regional scale, while the analysis of human intrusion involves phenomena occurring at the scale of a single waste package. As specified for the performance assessment, however, the entire range of potential spatial domains is *Included* in the TSPA–SR by specification of the various model boundaries.

The spatial domain of concern is also a function of the analysis that is being performed. For instance, the spatial domain of concern for the mechanisms leading to potential degradation of a waste package is much smaller than the spatial domain of concern for the mechanisms allowing hypothetical transport of radionuclides to a presumed point of exposure. Individual model domains are described in the documentation of each component of the TSPA model and in individual AMRs.

The spatial domain evaluated explicitly in the TSPA model extends from the land surface through the unsaturated zone, through the repository, into the saturated zone, and laterally away from the repository to the location of the exposure point. A significant health or environmental hazard may not be present throughout the entire area, but the entire area is considered to be within the domain of spatial concern of the performance assessment. For the primary purposes of the performance assessment, the encompassing spatial domain of concern for human intrusion includes all potential environmental pathways or radionuclide transport and exposure as proposed at 40 CFR §197.25 (64 FR 46976).

Related PMRs, AMRs, and Calculations: *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-00001 REV 00 (CRWMS M&O 2000c)

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

<u>Integrated Subissues/Related Subissues</u>

ENG2 Eng: Mechanical Disruption of Engineered Barriers/IA1, IA2, SDS1, SDS2, SDS3, SDS4
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC1, USFIC 3, USFIC4, TEF2, ENFE1, RDTME3
UZ2 Geo: Flow Paths in the UZ / USFIC4, TEF2, ENFE1, SDS3
UZ3 Geo: Radionuclide Transport in the UZ / USFIC4, USFIC6, ENFE4, SDS3
SZ1 Geo: Flow Paths in the SZ / USFIC1, USFIC4, USFIC5, SDS3, SDS4
SZ2 Geo: Radionuclide Transport in the SZ / USFIC5, USFIC6, SDS3
Direct1 Geo: Volcanic Disruption of Waste Packages / CLST1, CLST2, IA1, IA2
Direct2 Geo: Airborne Transport of Radionuclides / IA1, IA2,
Dose1 Bio: Dilution of Radionuclides in Groundwater / USFIC5
Dose2 Bio: Redistribution of Radionuclides in Soil/ IA2
Dose3 Bio: Lifestyle of the Critical Group / IA2

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Regulatory requirements and exclusions (0.1.09.00.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Model and data issues (0.1.10.00.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.2.3 Regulatory Requirements and Exclusions (0.1.09.00.00)

FEP Description: This FEP describes regulatory requirements and guidance specific to the Yucca Mountain repository.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion (for Primary FEP)

Excluded from the TSPA–SR—By Regulation (for Secondary FEPs)

Screening Argument: "Regulatory requirements and exclusions" is *Included* in the TSPA–SR as described under TSPA Disposition, for those regulations that are applicable to the Yucca Mountain Project. The Secondary FEPs are specific to WIPP and are, therefore, *Excluded.* Relevant aspects of the Secondary FEPs are addressed by other System-Level FEPs, specifically those dealing with atmospheric transport (see Section 6.2.30, "Atmospheric transport of contaminants" (3.2.10.00.00)).

TSPA Disposition: "Regulatory requirements and exclusions" is intrinsically *Included* in the TSPA. Regulatory requirements and exclusions provide the framework within which the TSPA is conducted. They define the performance criteria and provide assumptions that must be used in the evaluation (e.g., timescale of concern, characteristics of the reference biosphere, specification of a human-intrusion scenario, release limits to the accessible environment). They provide guidance on the features, events, and processes which must be considered (i.e., exclusion of low-probability and low-consequence-to-dose events) and limit the range of conditions which must be considered (e.g., "consistent with present knowledge of natural processes", "behaviors and characteristics" of the critical group, and the "form" of the human intrusion to be considered).

The various aspects of the repository including design, construction, operation, and preclosure and postclosure performance must be shown to comply with regulatory requirements. If not, the repository will not be licensed, construction may be prohibited, operations may be halted until deficiencies are corrected, or further operations or closure activities will be delayed until deficiencies are corrected.

The Secondary FEPs for this issue are particular to the WIPP project and are, therefore, *Excluded* from the TSPA–SR. The nature of the concerns for the Secondary FEPs (i.e., timescale of concern, future human behavior, and release limits to the accessible environments) are included as part of the TSPA–SR.

Supplemental Discussion: Proposed federal regulations applicable to the long-term performance of the disposal system are described at proposed rule

40 CFR 197 (64 FR 46976), and are presented at proposed rule 10 CFR 63 (64 FR 8640). Implementation of proposed rule 40 CFR 197 Subpart B Environmental Standards for Disposal (64 FR 46976) is the responsibility of the NRC.

At proposed rule 40 CFR §197.13 (64 FR 46976), the NRC is given the responsibility of determining "compliance based upon the mean or median (whichever is higher) of the highest results of DOE's performance assessments projecting the performance of the Yucca Mountain repository for 10,000 years after disposal." DOE must demonstrate a reasonable expectation that standards for the Individual-Protection Standard, Human-Intrusion Standard, and Ground Water Protection Standards will not be exceeded. Evaluation of compliance to these standards is the primary objective of the TSPA.

The criteria and assumptions to be used in making the evaluation are provided in the various referenced sections at proposed rules 10 CFR 63 (64 FR 8640) and proposed rule 40 CFR 197 (64 FR 46976) and are listed in Section 4.2 of this AMR. These criteria and assumptions are proposed regulatory requirements and have been incorporated into the TSPA model either using specified characteristics to guide selection of input parameters (such as the characteristics of the exposed group or individual) or by consideration of a range of possible climatic and geologic settings consistent with present knowledge of natural processes.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

<u>Integrated Subissues/Related Subissues</u>

None

Related Primary FEPs:

<u>Links to FEPs that examine related, but distinct, consequences and effects</u>:

Timescales of concern (0.1.02.00.00)
Spatial domain of concern (0.1.03.00.00)

<u>Links to FEPs that examine similar consequences and effects</u>:

Social and institutional developments (1.4.08.00.00)

Regulatory requirements and exclusions provide the framework within which the TSPA is conducted. They define the performance criteria and provide assumptions that must be used in the evaluation (e.g., characteristics of the reference biosphere, specification of a human-intrusion scenario). Consequently, in that sense, all FEPs are related to this Primary FEP.

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Assessment basis FEP (0.1.09.00.01)

Relationship to Primary FEP: The description indicates that compliance to regulatory requirements needs to be demonstrated. Corresponding YMP requirements concerning timescale of concern and future human behavior exist for YMP and are *Included* in the TSPA.

Screening and Disposition: *Excluded* from the TSPA–SR. The FEP description is particular to WIPP and to the related regulatory requirements.

Secondary FEP Name and Number: Assessment basis FEP (atmospheric processes) (0.1.09.00.02)

Relationship to Primary FEP: Corresponding YMP requirements concerning expected annual dose calculation exist for YMP and are *Included in* the TSPA–SR.

Screening and Disposition: *Excluded* from the TSPA–SR. The FEP description is particular to WIPP and to the related regulatory requirements.

6.2.4 Model and Data Issues (0.1.10.00.00)

FEP Description: This FEP describes issues identified by other programs related to modeling of the disposal system. Model and data issues are general (i.e., methodological) issues affecting the assessment modeling process and use of data. These issues include the approach and assumptions associated with the selection of conceptual models, the mathematical implementation of conceptual models, model geometry and dimensionality, models of coupled processes, and boundary and initial conditions. These issues also include the derivation of data values and correlations.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion (for Primary FEP and all Secondary FEPs, excluding unmodeled design features)

Excluded from the TSPA–SR—Low consequence to dose (for unmodeled design features)

Screening Argument: With regard to the Secondary FEP "Unmodeled design features," it is assumed that the repository will be constructed as designed, and that any modifications to the design will be thoroughly evaluated as specified by the proposed regulations (see Assumption 5.3 of this document, ANL-WIS-MD-000019). Therefore, any unmodeled design features that have a significant impact on performance will be detected and evaluated. Any remaining unmodeled features will, therefore, be of "low consequence to dose" and are excluded.

TSPA Disposition: "Model and data issues" and the related Secondary FEPs are intrinsically *Included* in the TSPA, with the exception of the Secondary FEP "Unmodeled design features." All of the remaining Secondary FEPs are *Included* in the TSPA–SR. "Model and data issues" are addressed specifically at proposed rule 10 CFR §63.114 (64 FR 8640,). The list of specifications for the performance assessment germane to "Model and data issues" includes paragraphs (a), (b), (c), and (g), which specify information and considerations that must be provided in the performance assessment.

Each of the models used in developing the TSPA has been documented according to project-specific QA procedures for model development, validation, and use. Model selection, use, verification, and inputs are addressed in the individual model AMRs. A discussion of the scope of the model and data issues addressed in the TSPA is provided in the TSPA–SR documentation (CRWMS M&O 2000c, Section 3) and in the various supporting PMRs for specific subject areas. The PMRs supporting the TSPA–SR specifically address the approach and assumptions, alternative approaches, the mathematical implementation of conceptual models, model geometry and dimensionality, models of coupled processes, boundary and initial conditions, and derivation of data values and correlations.

Supplemental Discussion: The specifications at proposed rule 10 CFR 63 (64 FR 8640, §63.114(a, b, c, and g)) pertinent to this FEP include the following clauses:

"(a) Include data related to the geology, hydrology, and geochemistry (including disruptive processes and events) of the Yucca Mountain site, and the surrounding region to the extent necessary, and information on the design of the engineered barrier system, used to define parameters and conceptual models used in the assessment." An overview of the scope of the models similar to those to be used for the TSPA is provided in CRWMS M&O (2000c, Section 3). The models and inputs being used address the Secondary FEP "Boundary conditions" and "Disposal geometry" and those dealing with "Correlation."

"(b) Account for uncertainties and variability in parameter values." Several kinds of uncertainties are distinguished and receive somewhat different treatments. These include: parameter uncertainty, conceptual model uncertainty, numerical model uncertainty, and future-event uncertainty. The TSPA recognizes and accounts for each type of uncertainty, where appropriate, and intends to provide the regulators with a basis for a "reasonable assurance" and a "reasonable expectation" of compliance. An overview of the treatment of uncertainty in the TSPA–SR is presented by CRWMS M&O (2000c, Sections 3 and 5). This discussion applies to multiple Secondary FEPs that deal with uncertainties.

"(c) Consider alternative conceptual models of features and processes." In many of the subsystems of the overall TSPA system, there are plausible alternative models or assumptions. In some cases, these alternative models form a continuum, and sampling from the continuum of assumptions fits naturally within the Monte Carlo framework of sampling from probability distributions. In other cases, the assumptions or models are based on discrete choices. Two possible approaches to incorporating alternative models within the TSPA include 1) weighting all models into one comprehensive Monte Carlo simulation (lumping), or keeping the discrete models separate and performing multiple Monte Carlo simulations for each discrete model (splitting). There are advantages and disadvantages to both approaches. A combination of the two approaches will be used, as described in CRWMS M&O (2000c, Sections 3 and 4). This approach addresses the Secondary FEP entitled "Conceptual model–hydrology"

"(g) Provide the technical basis for models used in the performance assessment such as comparisons made with outputs of detailed process-level models and/or empirical observations." Each of the models used in developing the TSPA has been documented according to project-specific QA procedures for model development, validation, and use. Model selection, use, verification, and inputs are addressed in the individual model AMRs. A discussion of the scope of the model and data issues addressed in the TSPA–SR is provided by CRWMS M&O (2000c, Section 3).

Related PMRs, AMRs, and Calculations: *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-00001 REV 00 (CRWMS M&O 2000c)

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

<u>Integrated Subissues/Related Subissues</u>

Affects All ISIs and KTIs

Related Primary FEPs:

<u>Links to FEPs that examine related, but distinct, consequences and effects</u>:

Timescales of concern (0.1.02.00.00)
Spatial domain of concern (0.1.03.00.00)
Waste-rock contact (2.1.09.11.00)
Rind (altered zone) formation in waste, EBS, and adjacent rock (2.1.09.12.00)
Temperature effects / coupled processes in waste and EBS (2.1.11.04.00)

Effects at material interfaces (2.1.06.07.00)
Locally saturated flow at bedrock/alluvium contact (2.2.07.01.00)

Links to FEPs that examine similar consequences and effects:

Undetected features in geosphere (2.2.12.00.00)

[Note: The Primary FEP is broad in its definition, Consequently, the list of related FEPs is not exhaustive. The listed FEPs were chosen based on elements within the Primary FEP description (geometry and dimensionality, coupled processes, boundary and initial conditions) and with regard to the Secondary FEPs. Any FEP addressed by models could potentially have been included within the list]

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Boundary conditions (0.1.10.00.01)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Uncertainties (repository) (0.1.10.00.02)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Correlation (0.1.10.00.03)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Uncertainties (geosphere) (0.1.10.00.04)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Correlation (0.1.10.00.05)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Uncertainties (biosphere) (0.1.10.00.06)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Model and data issues (0.1.10.00.07)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Unmodeled design features (0.1.10.00.08)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II

Screening and Disposition: *Excluded* from the TSPA–SR based on regulatory requirements (See Assumptions 5.2 and 5.3 of this document, ANL-WIS-MD-000019).

<u>*Secondary FEP Name and Number:*</u> Disposal geometry (0.1.10.00.09)

Relationship to Primary FEP: The specific description is pertinent only to the WIPP performance assessment. However, the use of models is pertinent to YMP, and the FEP is, therefore, retained. Subcategory within Primary FEP description, see Attachment II

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Conceptual model hydrology (0.1.10.00.10)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>Secondary FEP Name and Number:</u> Correlation (contaminant speciation and solubility) (0.1.10.00.11)

Relationship to Primary FEP: Subcategory within Primary FEP description, see Attachment II

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

6.2.5 Records and Markers, Repository (1.1.05.00.00)

FEP Description: This category contains FEPs related to the retention of records of the contents of the repository and markers constructed to inform future humans of the location and contents of the repository. Performance assessments must consider the potential effects of human activities that might take place within the controlled area at a future time when institutional controls and/or knowledge of the presence of a repository cannot be assumed.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion (for construction of markers to inform future humans of the location and contents of the repository, retention of records, and for lack of knowledge of the repository at future times)

Excluded from the TSPA–SR—By Regulation
(for efficacy of markers and record retention to prevent intrusion after 100-years postclosure)

Screening Argument: The guidance and criteria specified in Section 4.2.4 describe the type of future human intrusion that must be considered for the Yucca Mountain repository. Proposed rule 10 CFR 63 specifies that a human intrusion occurs (64 FR 8640, §63.102(k) and (l)) and specifies the time at which it occurs (64 FR 8640, §63.113(d)). Furthermore, it specifies that the TSPA must consider the consequences of a human intrusion, regardless of the state of future human knowledge of the site (64 FR 8640, §63.102(k) and (l)).

The proposed regulatory requirement to evaluate a stylized human-intrusion scenario in the TSPA renders nil the efficacy of markers and retention of site knowledge; therefore, consideration of efficacy is *Excluded* based on the proposed regulatory requirement.

TSPA Disposition: "Records and markers, repository" is *Included* in the TSPA. Proposed rule 10 CFR §63.113(d) (64 FR 8640) carries two suppositions:

(1) that for the first 100 years after closure, active and/or passive controls are sufficient to effectively prevent intrusion, and

(2) that after the first 100 years, records and markers are lost, ignored, or ineffective in preventing the intrusion.

The markers and records will certainly persist for some portion of the regulatory period, and for the purposes of the TSPA are assumed to be effective to prevent human intrusion for 100 years following repository closure (See Assumption 5.4 of this document, ANL-WIS-MD-000019). They are, therefore, considered as *Included* in the TSPA–SR in that respect. An assumed effectiveness for 100 years also addresses the questions of efficacy raised in Secondary FEP "Repository records, markers."

Markers will be constructed at the site, and long-term records will be prepared and maintained consistent with the NRC proposed regulations. The specifications for constructing monuments and for preserving records in archives, and the list of records to be maintained, are listed at proposed rule 10 CFR 63 (64 FR 8640, §63.51(a)(3)(i-iii); §63.72(a); and §63.72(b)(1-11), respectively).

Supplemental Discussion: The stylized human-intrusion scenario approach was taken to avoid speculating on the nature and probability of future intrusion and because it is not possible to make scientifically sound forecasts of the long-term reliability of active and passive institutional controls. In effect, this approach renders nil speculation about the possible future loss of societal knowledge and effectiveness of the role of markers and records in preventing human intrusion of the site after the initial 100-year period.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>*Directly Affected Subissues*</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening

<u>*Integrated Subissues/Related Subissues*</u>

ENG2 Eng: Mechanical Disruption of Engineered Barriers / CLST2, CLST6, RDTME1

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Deliberate human intrusion (1.4.02.01.00)
Inadvertent human intrusion (1.4.02.02.00)
Mining and other underground activities (1.4.05.00.00)
Urban and industrial land and water use (2.4.10.00.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Administrative control, repository site (1.1.10.00.00)
Social and institutional developments (1.4.08.00.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Loss of Records (1.1.05.00.01)

Relationship to Primary FEP: Redundant with Primary FEP, retained for completeness
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Repository records, markers (1.1.05.00.02)

Relationship to Primary FEP: Description refers to retention of records.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Loss of records (1.1.05.00.03)

Relationship to Primary FEP: No description in source document, inferred to be redundant with Primary FEP, retained for completeness
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Loss of records (1.1.05.00.04)

Relationship to Primary FEP: Redundant with Primary FEP, retained for completeness
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

6.2.6 Repository Design (1.1.07.00.00)

FEP Description: This category contains FEPs related to the design of the repository, and the ways in which the design contributes to long-term performance. Changes to or deviations from the specified design may affect the long-term performance of the disposal system.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion (for licensed repository design and for design modifications)

Excluded from the TSPA–SR—Low consequence to dose (for significant undetected deviations from design),

Excluded from the TSPA–SR—By Regulation
(for inadequacy or lack of safety of the proposed design and for non-YMP design elements)

Screening Argument: The TSPA is based on an assumption that the repository will be constructed, operated, and closed according to design under an acceptable quality control plan (see Assumption 5.3 of this document, ANL-WIS-MD-000019). Modifications and/or deviations from the design will be subject to regulatory requirements and review that address deliberate design changes (64 FR 8640, §63.31 and §63.33). In particular, proposed rule 10 CFR §63.73(a) (64 FR 8640) specifies prompt notification if there is a significant deficiency found (1) in the characteristics of the Yucca Mountain site, or (2) in design and construction of the geologic repository area, including significant deviations from the design criteria and design bases stated in the application. Furthermore, proposed rule 10 CFR 63 (64 FR 8640, Subpart F) provides a list of specifications for a performance confirmation program to confirm design parameters and to ensure that the NRC is informed of changes needed in the design to accommodate actual field conditions. These specifications ensure a low consequence to dose (it is unlikely that there will be significant effects from undetected deviations) in the event that the design is not followed.

Significant deviations from the design that are detected during the operational period will be corrected and, therefore, are *Excluded* from the TSPA–SR based on a low consequence to dose. Additionally, portions of the Secondary FEPs dealing with the inadequacy or lack of safety of a proposed design are precluded by assumptions, guidance, or criteria at the proposed regulations and are *Excluded* from specific consideration in the TSPA–SR based on the proposed regulatory requirements. This dual-based exclusion ("low consequence to dose" and "regulatory") specifically applies to the Secondary FEPs "Poorly designed repository" (1.1.07.00.01) and "Design and construction FEPs" (1.1.07.00.06 and 1.1.07.00.08).

Several of the remaining Secondary FEPs are specific to other project designs and are not directly applicable to the Yucca Mountain Project (YMP). Because they are not applicable to YMP, they are *Excluded* from the TSPA–SR based on regulation. (See Table 4 for list of the Secondary FEPs). This applies to the Secondary FEPs "HLW panels (siting) (1.1.07.00.03), "TRU silos (siting)" (1.1.07.00.04), and "Access tunnels and shafts" (1.1.07.00.05).

TSPA Disposition: "Repository design" and potential design modifications are *Included* in the TSPA–SR. The design elements are included as nominal-scenario parameters used to define the physical dimensions, the characteristics, and the behavior of the waste form, waste packages, and the engineered barrier system. It is assumed that the repository will be constructed, operated, and closed according to the design used as the basis for the FEP screening, and that the repository will be constructed, operated, and closed according to applicable NRC regulatory requirements during the preclosure period (see Assumption 5.3 of this document, ANL-WIS-MD-000019). This applies to the Secondary FEPs "Design modification" (1.1.07.00.02) and "Design and construction" (1.1.07.00.07).

Supplemental Discussion: In general, the TSPA is based on an assumption that the repository will be constructed, operated, and closed according to design (see Assumption 5.3 of this document, ANL-WIS-MD-000019). If the repository does not meet regulatory criteria it will not be licensed, and waste will not be emplaced.

Confirmation of design parameters and informing the NRC of any changes needed in the design to accommodate actual field conditions are subjects of the performance confirmation as specified at proposed rule 10 CFR 63 (64 FR 8640, Subpart F). These specifications provide for confirmation of geotechnical and design parameters; design testing; and the monitoring and testing of waste packages to be performed during the construction and operational period.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME1: Design Control Processes Within the Overall Quality Assurance Program
RDTME2: Design of for the Effects of Seismic Events and Direct Fault Disruption
RDTME3: Thermal Mechanical Effects on Underground Facility Design and Performance
RDTME4: Design and Long Term Contribution of Repository Seals.

Integrated Subissues/Related Subissues

ENG1 Eng: Degradation of Engineered Barriers / CLST1, CLST2, CLST6
ENG2 Eng: Mechanical Disruption of Barriers / CLST1, CLST2, CLST5, CLST6, IA2, SDS1, SDS2
ENG3 Eng: Quantity and Chemistry of Water Contacting the Waste Packages and Waste Forms / CLST1, CLST3, CLST4, CLST6
ENG4 Eng: Radionuclide Release Rates and Solubility Limits / ENFE2, ENFE3, ENFE5, CLST5
Direct1 Geo: Volcanic Disruption of Waste Packages / IA2
Direct2 Geo: Airborne Transport of Radionuclides / IA2

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Quality control (1.1.08.00.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

None

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Poorly designed repository (1.1.07.00.01)

Relationship to Primary FEP: This Secondary FEP is precluded by regulatory criteria, which require that any deviations from design be evaluated and require demonstration of safety of the repository.
Screening and Disposition: Excluded from the TSPA–SR—Low consequence to dose and By Regulation

<u>*Secondary FEP Name and Number:*</u> Design modification (1.1.07.00.02)

Relationship to Primary FEP: No description in the source documentation, inferred to be addressed by regulatory requirements to address design changes.
Screening and Disposition: Included in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> HLW panels (siting) (1.1.07.00.03)

Relationship to Primary FEP: This FEP describes a project-specific geometry other than the YMP. The concept of set-backs is used for the YMP preclosure design and is included in the geometry used for the TSPA–SR.
Screening and Disposition: Excluded from the TSPA–SR—By Regulation. This FEP describes a project-specific geometry other than the YMP.

<u>*Secondary FEP Name and Number:*</u> TRU silos (siting) (1.1.07.00.04)

Relationship to Primary FEP: This FEP describes a project-specific geometry other than the YMP. Retained in FEPs list for completeness.
Screening and Disposition: Excluded from the TSPA–SR—By Regulation This FEP describes a project-specific geometry other than the YMP.

<u>*Secondary FEP Name and Number:*</u> Access tunnels and shafts (1.1.07.00.05)

Relationship to Primary FEP: This FEP describes a project-specific geometry other than the YMP. Retained in FEPs list for completeness.
Screening and Disposition: Excluded from the TSPA–SR—By Regulation This FEP describes a project-specific geometry other than the YMP.

Secondary FEP Name and Number: Design and construction FEPs (1.1.07.00.06)

Relationship to Primary FEP: This Secondary FEP is precluded by regulatory criteria, which require that any deviations from design, be evaluated and require demonstration of safety of the repository.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose and By Regulation

Secondary FEP Name and Number: Design and construction (1.1.07.00.07)

Relationship to Primary FEP: No description in the source documentation, assumed to be addressed be regulatory requirements to address adequacy and safety of the proposed design and to address design changes.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Design and construction FEPs (1.1.07.00.08)

Relationship to Primary FEP: Redundant with (1.1.07.00.06) and retained in FEPs list for completeness
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose and By Regulation

6.2.7 Quality Control (1.1.08.00.00)

FEP Description: This category contains FEPs related to quality assurance and control procedures, and tests during the design, construction, and operation of the repository, as well as the manufacture of the waste forms, containers, and engineered features. Lack of quality control could result in material defects, faulty waste package fabrication, and faulty or non-design-standard construction, all of which may lead to reduced effectiveness of the engineered barriers.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy screening criterion (for Primary FEP and for Secondary FEPs 1.1.08.00.05 and 1.1.08.00.06)

Excluded from the TSPA–SR—Low consequence to dose (for the Secondary FEPs addressing material defects, faulty fabrication, and faulty or non-design-standard construction)

Excluded from the TSPA–SR—By Regulation (for Secondary FEPs addressing the installation of panel, silos, and drains)

Screening Argument: The TSPA is based on an assumption that the repository will be constructed, operated, and closed according to design (See Assumption 5.3 of this document, ANL-WIS-MD-000019).

Deviations from design during the operational period are subjects of an extensive performance confirmation plan (64 FR 8640 Subpart F) and corresponding quality control program (64 FR 8640, Subpart G). Furthermore, Subpart G specifies that DOE "implement a quality assurance program based on the criteria of Appendix B of 10 CFR 50, as applicable, and appropriately supplemented by additional criteria, as required by Sec. 142." The quality assurance program is to be applied to all systems, structures, and components important to safety and to design and characterization of barriers important to waste isolation. Proposed rule 10 CFR §63.73(a) (64 FR 8640) specifies prompt notification if there is a significant deficiency found. Significant deviations that are detected during the operational period will be corrected. Any residual defects or fabrication or construction deficiencies will, therefore, be of a minor nature and will not lead to significant effects on the repository performance. If repository performance is not affected, there is no impact to the expected annual dose. Therefore, the FEP is *Excluded* based on low consequence to dose.

In the same manner, the Secondary FEPs "Poorly constructed repository" (1.1.08.00.01), "Material defects" (1.1.08.00.02), "Common cause failures" (1.1.08.00.03), and "Poor quality construction" (1.1.08.00.04) are *Excluded* from the TSPA–SR based on low consequence to dose. The Secondary FEP (1.1.08.00.07) that addresses the installation of panel, silos, and drains is irrelevant to YMP because it is not a design element for YMP and is, therefore, *Excluded* from the TSPA–SR based on regulation (see Assumption 5.3 of this document, ANL-WIS-MD-000019).

Regardless of the requirements of the quality assurance and performance confirmation programs, the TSPA allows for the possibility that engineered systems may not perform entirely as designed for the full 10,000 years, through the probabilistic treatment of waste-package degradation.

TSPA Disposition: The primary FEP "Quality control" and the two secondary FEPs titled "Quality control" (1.1.08.00.05 and 1.1.08.00.06) are *Included* in the TSPA–SR.

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, and that the repository will be constructed, operated, and closed according to the regulatory requirements in effect during the preclosure period (See Assumption 5.3 of this document, ANL-WIS-MD-000019). This includes the implementation of specified performance-confirmation and quality-assurance programs Quality control considerations are implicitly *Included* in the TSPA–SR models through the use of parameters that define the behavior of the various repository components (i.e., such as corrosion rates and seismic fragility) that were derived from known design standards and features (e.g., types of materials, mechanical response to vibratory loading).

Consequently, the Primary FEP and the two Secondary FEPs all titled "Quality control" are considered as *Included* in the TSPA–SR.

Supplemental Discussion: See preceding *Screening Argument* and *TSPA Disposition* discussions.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>*Directly Affected Subissues*</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME1: Design Control Process Within the Overall Quality Assurance Program

<u>*Integrated Subissues/Related Subissues*</u>

Affects all design-related ISIs and KTIs

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Retrievability (1.1.13.00.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Waterlogged rods (2.1.02.11.00)
Undesirable materials left (1.1.02.03.00)
Error in waste or backfill emplacement (1.1.03.01.00)
Incomplete closure (1.1.04.01.00)
Juvenile and early failure of waste containers and drip shields (2.1.03.08.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Poorly constructed repository (1.1.08.00.01)

Relationship to Primary FEP: This is a particular type of quality control issue and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

Secondary FEP Name and Number: Material defects (1.1.08.00.02)

Relationship to Primary FEP: This is a particular type of quality control issue and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

Secondary FEP Name and Number: Common cause failures (1.1.08.00.03)

Relationship to Primary FEP: This is a particular type of quality control issue and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

Secondary FEP Name and Number: Poor quality construction (1.1.08.00.04)

Relationship to Primary FEP: This is a particular type of quality control issue and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

Secondary FEP Name and Number: Quality control (1.1.08.00.05)

Relationship to Primary FEP: Description addresses the need for quality control of glass. The Primary FEP description includes quality control on manufacture of waste packages.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Quality control (1.1.08.00.06)

Relationship to Primary FEP: Description addresses the need for quality control of canisters. The Primary FEP description includes quality control on manufacture of waste packages.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Drains, installed to divert water around containers are improperly placed (1.1.08.00.07)

Relationship to Primary FEP: The FEP addresses elements that are not part of the YMP design.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

6.2.8 Schedule and Planning (1.1.09.00.00)

FEP Description: This category contains FEPs related to the sequences of events and activities occurring during construction, operation, and closure of the repository. Deviations from the design construction or waste emplacement schedule may affect the long-term performance of the disposal system.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—By Regulation

Screening Argument: "Schedule and planning" is *Excluded* from the TSPA–SR based on regulation.

The objective of the TSPA is to evaluate compliance with the *postclosure* performance objective. Scheduling and planning are preclosure operational issues and are outside the scope of the TSPA as described at proposed rule 10 CFR 63 (64 FR 8640, §63.102(j)). The Secondary FEP "Effects of phased operation" also deals with preclosure concerns and is, therefore, *Excluded.*
In general, the TSPA is based on an assumption that the repository will be constructed, operated, and closed according to the design schedule (see Assumption 5.3 of this document, ANL-WIS-MD-000019). Events related to changes in the construction schedule are outside the scope of the TSPA.

TSPA Disposition: "Schedule and planning" and all secondary FEPs are *Excluded* from the TSPA–SR as described under the Screening Argument.

Supplemental Discussion: See Screening Arguments

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME1: Design Control Process Within the Overall Quality Assurance Program

Integrated Subissues/Related Subissues

None

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

None

Links to FEPs that examine similar consequences and effects:

None

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Effects of phased operation (1.1.09.00.01)

Relationship to Primary FEP: No description in source document, retained in FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA-SR—By Regulation

6.2.9 Administrative Control, Repository Site (1.1.10.00.00)

FEP Description: This category contains FEPs related to administrative control of the repository site. Administrative control can reduce the possibility that human activities might take place within the controlled area.

Screening Decision and Regulatory Basis: *Included* in the TSPA-SR—Does not satisfy a screening criterion (for administrative control during preclosure period, for initial construction of markers and archiving of records, for subsequent loss of administrative control, and for Secondary FEPs)

Excluded from the TSPA-SR—By Regulation
(for efficacy of administrative controls beyond 100 years of the postclosure period)

Screening Argument: Proposed rule 10 CFR §63.113(d) (64 FR 8640) specifies that a human intrusion event occurring 100 years after closure be evaluated. By specifying that a human intrusion occurs (64 FR 8640, §63.102(k) and (l)), and by specifying a time at which it occurs (64 FR 8640, §63.113(d)), the proposed rule carries two suppositions:

(1) that for the first 100 years after closure, active and/or passive controls are sufficiently effective in preventing intrusion and,

(2) that after the first 100 years that records and markers are lost, ignored, or ineffective in preventing the intrusion.

Proposed rule 40 CFR 197 (64 FR 46976, §197.25 and §197.26) states that DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers, or assume that an intrusion occurs at a time or within a range of time determined by the NRC. The NRC is directed to make the determination based on three factors: (1) the earliest time that current drilling techniques could lead to waste penetration without recognition by the drillers, (2) the time for a small percentage of waste packages to fail but prior to significant migrations, and (3) the intrusion not occurring during the period of active institutional control.

Accordingly, any evaluation of exposures based on a human-intrusion scenario occurring at a specified time inherently includes suppositions about the effectiveness of institutional controls as part of the analysis (Assumption 5.4 of this document, ANL-WIS-MD-000019). In effect, the proposed regulatory requirement to use a stylized human-intrusion scenario renders nil any speculation about the possible future loss of societal knowledge and effectiveness of active institutional control (or administrative control) in preventing human intrusion of the site after the initial 100-year period.

TSPA Disposition: "Administrative control, repository site" is *Included* in the TSPA–SR for initial construction of markers and archiving of records, for subsequent loss of administrative control, and for Secondary FEPs. Markers will be constructed at the site and long-term records will be prepared and maintained consistent with the proposed rule 10 CFR 63 (64 FR 8640, §63.72(a) and (b)(1-11)). The specifications for constructing monuments, preserving and archiving records, and oversight are listed at proposed rule 10 CFR §63.51(a)(3)(i-iii) (64 FR 8640). The markers and repository will certainly persist for some portion of the regulatory period. Land ownership and control requirements are specified by proposed rule 10 CFR §63.121 (64 FR 8640)). The Secondary FEP "Planning restriction" is also *Included* in the TSPA–SR because the loss of administrative control after 100 years is implicit in the regulation.

Supplemental Discussion: Proposed rule 10 CFR 63 (64 FR 8640, §63.102(k) and (l)) specifies that the TSPA must consider the consequences of a human intrusion, regardless of the state of future human knowledge of the site. The guidance specifies the type of future human intrusion that must be considered for the Yucca Mountain repository (64 FR 8640, §63.113(d)) and specifies that the event occurs 100 years after permanent closure. This stylized approach was taken to avoid speculating on the nature and probability of future intrusion and because it is not possible to make scientifically sound forecasts for the long-term reliability of active and passive institutional controls.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>*Directly Affected Subissues*</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
RDTME1; Design Control Process Within the Overall Quality Assurance Program
RDTME3: Underground Facility Design and Performance

<u>*Integrated Subissues/Related Subissues*</u>

None

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects:*</u>

Deliberate human intrusion (1.4.02.01.00)
Inadvertent human intrusion (1.4.02.02.00)
Unintrusive site investigation (1.4.03.00.00)
Drilling activities (human intrusion) (1.4.04.00.00)
Mining and other underground activities (1.4.05.00.00)
Altered soil or surface water chemistry (1.4.06.01.00)
Explosions and crashes (1.4.11.00.00)
Urban and industrial land and water use (2.4.10.00.00)

<u>*Links to FEPs that examine similar consequences and effects:*</u>

Records and markers, repository (1.1.05.00.00)
Social and institutional developments (1.4.08.00.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Planning restrictions (1.1.10.00.01)

Relationship to Primary FEP: The description for the secondary FEP (see Attachment II) indicates that the safety of the repository must not rely on administrative controls. As stated, it is the opposite statement from that made in the Primary FEP description. This leads to the mixed *Included/Excluded* Screening Decision for the Primary FEP.

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

6.2.10 Monitoring of Repository (1.1.11.00.00)

FEP Description:

This category contains FEPs related to monitoring that is carried out during or after operations, for either operational safety or verification of long-term performance. Monitoring boreholes could provide enhanced pathways between the surface and the repository.

Screening Decision and Regulatory Basis:

Excluded from the TSPA–SR—Low consequence to dose
(for Primary and Secondary FEPs, with the exception of the Secondary FEP "Monitoring and remedial activities" (1.1.11.00.01))

Included in the TSPA–SR—Does not satisfy a screening criterion (for monitoring wells and boreholes as addressed by the human-intrusion scenario and for Secondary FEP "Monitoring and remedial activities" (1.1.11.00.01))

Screening Argument: "Monitoring of repository" and the Secondary FEPs are *Excluded* from the TSPA–SR based on low consequence to dose. Any monitoring program must be implemented so that it "does not adversely affect the ability of the geologic and engineered elements of the geologic repository to meet the performance objectives" (64 FR 8640, §63.131(d)(1)). If the geologic repository is not adversely affected, then the dose is not significantly changed. Therefore, monitoring activities are *Excluded* based on low consequence to dose.

TSPA Disposition: The Secondary FEPs raise concerns about post-closure monitoring activities, primarily related to the use of monitoring wells, as described for Secondary FEP "Monitoring and remedial activities" (1.1.11.00.01). All boreholes and monitoring wells will be drilled and sealed in accordance with regulatory specifications effective during the preclosure period (see Assumption 5.3 of this document, ANL-WIS-MD-000019), and boreholes should have no impact on the repository performance. Once properly sealed, there should be no effect on groundwater flow systems. Regardless, installation or improper sealing of a borehole or monitoring well is analogous to the human-intrusion scenario.

By analogous reasoning, the human-intrusion scenario provides a measure of the level of consequence of any intentional intrusion or inadvertent omission of sealing monitoring points near the repository at the end of the institutional control period. By analogy, monitor wells or boreholes are, in effect, included within the human-intrusion scenario. Therefore, the effect of monitoring boreholes and wells is subsumed within the human-intrusion scenario and is deemed to be *Included* in the TSPA–SR.

Supplemental Discussion: It is assumed (see Assumption 5.3 of this document, ANL-WIS-MD-000019) that the monitoring activities will be conducted as required by regulations, and that all boreholes and monitoring wells will be sealed as required by regulation prior to the end of institutional controls. The use of a monitoring well for other than intended purposes is addressed by the use of institutional controls to prevent access to the wells prior to the time of the human intrusion.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
RDTME1; Design Control Process Within the Overall Quality Assurance Program
RDTME3: Underground Facility Design and Performance

Integrated Subissues/Related Subissues

None

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Drilling activities (human intrusion) (1.4.04.00.00)
Effects of drilling intrusion (1.4.04.01.00)

Links to FEPs that examine similar consequences and effects:

Open site investigation boreholes (1.1.01.01.00)
Loss of integrity of borehole seals (1.1.01.02.00)
Abandoned and undetected boreholes (1.4.04.02.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Monitoring and remedial activities (1.1.11.00.01)

Relationship to Primary FEP: FEP description generically raises potential for borehole as pathway for contaminant transport, which is analogous to the human-intrusion scenario.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition through the human-intrusion scenario

Secondary FEP Name and Number: Postclosure monitoring (1.1.11.00.02)

Relationship to Primary: Description specifically calls out "short path to biosphere" and use as water supply, which is in conflict with the regulatory definitions and assumptions specified for YMP, and is precluded by regulatory requirements for YMP.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

Secondary FEP Name and Number: Post-closure monitoring (1.1.11.00.03)

Relationship to Primary FEP: No description in source document, inferred to be redundant, retained in FEPs list for completeness
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

Secondary FEP Name and Number: Postclosure monitoring (1.1.11.00.04)

Relationship to Primary FEP: Description is specific to WIPP. By regulation, monitoring activities must not adversely affect the repository performance.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

6.2.11 Accidents and Unplanned Events During Operation (1.1.12.01.00)

FEP Description: The long-term performance of the disposal system might be seriously affected by unplanned or improper activities that take place during construction, operation, and closure of the repository.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—Low consequence to dose (for Primary and Secondary FEPs), By Regulation for "Sabotage and improper operation (1.1.12.01.02)"

Screening Argument: "Accidents and unplanned events during operation" and all Secondary FEPs are *Excluded* from the TSPA–SR based on low consequence to dose.

Operations will be according to procedures acceptable to the NRC and EPA. Quality control procedures and performance confirmation are designed to detect operational events resulting in deviations from the repository design that might affect long-term performance. Any deviation would presumably be detected during regulator audits and inspections (see 64 FR 8640, Subpart F) and be corrected before further work in the repository would be allowed to continue. Therefore, accidents and unplanned events during the operational phase would not have a significant effect on long-term performance and are *Excluded* from the TSPA–SR based on low consequence to dose. The Secondary FEPs related to accidents and unplanned events are *Excluded* from the TSPA–SR based on low consequence to dose. The Secondary FEP "Sabotage and improper operation" is *Excluded* from the TSPA–SR because sabotage is a form of "Deliberate human intrusion" (1.4.02.01.00) and is, therefore, *Excluded* from the TSPA–SR based on regulation.

TSPA Disposition: "Accidents and unplanned events during operation" are *Excluded* from the TSPA–SR as described under the Screening Argument.

Supplemental Discussion Proposed rule 10 CFR §63.73(a) (64 FR 8640) specifies prompt notification if there is a significant deficiency found in the characteristics of the Yucca Mountain site, and design and construction of the geologic repository area, including significant deviations from the design criteria and design bases stated in the application (Assumption 5.3 of this document, ANL-WIS-MD-000019). If the repository does not meet regulatory criteria, it will not be licensed, and waste will not be emplaced.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>*Directly Affected Subissues*</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME: Design Control Process Within the Overall Quality Assurance Program
RDTME3: Underground Facility Design and Performance

<u>*Integrated Subissues/Related Subissues*</u>

ENG1 Eng: Degradation of Engineered Barriers / CLST1, CLST2, CLST6
ENG2 Eng: Mechanical Disruption of Barriers / CLST1, CLST2, CLST5, CLST6

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Deliberate human intrusion (1.4.02.01.00)
Repository design (1.1.07.00.00)

Quality control (1.1.08.00.00)
Retrievability (1.1.13.00.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Site flooding (1.1.02.01.00)
Undesirable materials left (1.1.02.03.00)
Explosions and crashes (1.4.11.00.00)
Mechanical impact on waste container and drip shield (2.1.03.07.00)
Gas explosion (2.1.12.08.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Preclosure events (1.1.12.01.01)

Relationship to Primary FEP: Addresses unplanned events and gives specific examples of preclosure and the consequences of postclosure.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

<u>*Secondary FEP Name and Number:*</u> Sabotage and improper operation (1.1.12.01.02)

Relationship to Primary FEP: Invokes consideration of "improper operation", and is, therefore, addressed in this Primary FEP. Sabotage is a form of deliberate human intrusion.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Accidents during operation (1.1.12.01.03)

Relationship to Primary FEP: The FEP description is focused on the consequence resulting from an accident and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose.

Secondary FEP Name and Number: Accidents during operation (1.1.12.01.04)

Relationship to Primary FEP: No description in source document, retained in FEPs list for completeness
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

Secondary FEP Name and Number: Handling accidents (1.1.12.01.05)

Relationship to Primary FEP: Specifically applies to handling accidents. Handling is a preclosure consideration that could affect long term performance and is, therefore, included in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

Secondary FEP Name and Number: Oil or organic fluid spill (1.1.12.01.06)

Relationship to Primary FEP: Specific type of spills are described. Spills are unplanned and are, therefore, included in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR

6.2.12 Retrievability (1.1.13.00.00)

FEP Description: This category contains FEPs related to design, emplacement, operational, or administrative measures that might be applied or considered in order to enable or ease retrieval of wastes. There may be a requirement to retrieve all or part of the waste stored in the repository, for example, to recover valuable fissile materials or to replace defective containers.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion (for Primary and Secondary FEPs related to design elements and emplacement)

Excluded from the TSPA–SR—By Regulation
(for operational and administrative considerations)

Screening Argument: "Retrievability" with regard to design elements and emplacement (e.g., dimensions of the drift and waste package design) is *Included* in the TSPA–SR as described under TSPA Disposition. The operational and administrative considerations of "Retrievability" are a preclosure consideration and are, therefore, *Excluded* from TSPA evaluation. The objective of the performance assessment is to evaluate compliance with the *postclosure* performance objective (64 FR 8640, §63.102(j)).

TSPA Disposition: "Retrievability" is a performance objective of the repository as specified at proposed rule 10 CFR §63.111(e)(1-3) (64 FR 8640).

This guidance specifies that the repository be designed in such a way that it preserves ". . . the option of waste retrieval throughout the period during which wastes are being emplaced . . . so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated . . . ." Aspects of the repository design related to waste retrievability (such as the design of the drifts and emplacement of the waste packages) are used as the basis for the TSPA modeling. Retrievability is thereby implicitly *Included* in the TSPA.

Postclosure retrieval of wastes or other repository-system components are considered a deliberate human intrusion and are *Excluded* from the TSPA–SR as discussed in Section 6.2.17 of this document (ANL-WIS-MD-000019).

Supplemental Discussion: See TSPA Disposition

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME: Design Control Process Within the Overall Quality Assurance Program
RDTME3: Underground Facility Design and Performance

Integrated Subissues/Related Subissues

None

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Deliberate human intrusion (1.4.02.01.00)

Mining and underground activity (human intrusion) (1.4.05.00.00)

Links to FEPs that examine similar consequences and effects:

Repository design (1.1.07.00.00)
Quality control (1.1.08.00.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Retrievability (1.1.13.00.01)

Relationship to Primary FEP: Basis of Primary FEP
Screening and Disposition: Same as Primary FEP

6.2.13 Metamorphism (1.2.05.00.00)

FEP Description: This category includes FEPs related to regional metamorphism, which has the potential to affect the long-term performance of the repository if it occurs. Metamorphic activity is defined as solid state recrystallization changes to rock properties and geologic structures through the effects of heat and/or pressure.

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

Screening Argument: "Metamorphism" is *Excluded* from the TSPA–SR based on low consequence to dose. For purposes of the FEP screening, the discussion is limited to regional scale and contact metamorphism.

The NEA definition of metamorphism refers to the processes by which rocks are changed by the action of heat (T>200°C) and pressure at depths (usually several kilometers and at pressures on the order of a few thousand kilobars) beneath the Earth's surface (referred to herein as *regional metamorphism*) or in the vicinity of magmatic activity (referred to herein as *contact metamorphism*). Changes in sediments and rocks at lesser conditions are referred to as *diagenesis* (see Section 6.2.14 "Diagenesis" (1.2.08.00.00)). (See Bates and Jackson (1984, p. 137) and Berry and Mason (1959, p. 240) for additional definitions).

Regional metamorphism is dependent on regional tectonic deformation at Yucca Mountain and is, therefore, dependent on the strain accumulation rates and on slip rates. Savage et al. (1999, p. 17627) presents an evaluation of the strain accumulation rate at Yucca Mountain, Nevada, for the period of 1983 to 1998 and addresses alternate interpretations indicating higher strain rates presented by Wernicke et al. (1998). The strain rate in the Yucca Mountain area is very low (2 nanostrain/yr: Savage et al. 1999, p. 17627). Whether the strain rates from Savage et al. or Wernicke et al. are considered, the strain rate has resulted in cumulative fault slip rates of 0.001–0.03 mm/yr (CRWMS M&O 2000e, Table 6). These low strain rates and local cumulative fault slip rates suggest the mechanisms leading to metamorphic activity, deep burial in particular, will also occur at a slow rate.

The rate of subsidence (vertical movement leading to deep burial) will be controlled by movement along the block-bounding faults and, at maximum, approximates the cumulative rate of fault slip at Bare Mountain and Yucca Mountain. The local cumulative fault slip rate is low (0.001–0.03 mm/yr) (CRWMS M&O 2000e, Table 6). A slip rate of 0.03 mm/yr would result in a vertical movement of only approximately 30 meters in a one-million-year period. The geothermal gradient, measured in borings 300 m to 600 m deep, is approximately 30°C/km (Sass et al. 1988, pp. 38-39). A typical value for pressure gradients from geostatic loading is about 285 bars/km (Hyndman 1972, pp. 270-273). A 30-m vertical movement is insufficient to result in pressure and temperature conditions conducive to regional metamorphism. Additionally, the locus of subsidence has moved to the southwest corner of the basin, away from Yucca Mountain (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 Secondary FEPs are also *Excluded* from the TSPA–SR based on low consequence to dose.

Contact metamorphism is by definition associated with igneous activity. Contact metamorphism is more fully addressed under "Igneous activity causes changes to rock properties" (1.2.04.02.00) in the *YMP FEP Database* (CRWMS M&O 2000d, Appendix D; and CRWMS M&0 2000f, Section 6.2.9) and is *Excluded.* Natural-analogue studies at the Nevada Test Site (Paiute Ridge and Grant's Ridge sites) show that alteration (e.g.,, at the contact of the host rock with an intrusive body) is limited to less than 10 meters away from the contact (Valentine et al. 1998, p. 5-41). Valentine et al. (1998, p. 5-42) states: "Based on natural analog 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." Alteration, brecciation, and deformation are related to contact metamorphic processes. The natural-analogue studies indicate that, were contact metamorphism to occur, it would affect only areas immediately adjacent to the dike. Because of the minimal area affected, there is no mechanism by which contact metamorphism would significantly affect dose. Contact metamorphism is, therefore, *Excluded* from the TSPA–SR based on low consequence to dose.

In summary, metamorphism refers to the processes by which rocks are changed by the action of heat (T>200°C) and pressure at depths (usually several kilometers and at pressures on the order of a few thousand kilobars) beneath the Earth's surface or in the vicinity of magmatic activity. Regional metamorphism requires significantly increased pressure (generally resulting from burial on the order of thousands of meters), increased temperatures (T>200°C) and long periods of geologic time (millions of years) to occur. At Yucca Mountain, development of these conditions would be dependent on the rate of active tectonism and would require several million years to develop. Contact metamorphism is more fully addressed under "Igneous activity causes changes to rock properties" (1.2.04.02.00) in the *YMP FEP Database* (CRWMS M&O 2000d, Appendix D), and is *Excluded* based on low consequence to dose. Natural-analogue studies at the Nevada Test Site (Paiute Ridge and Grant's Ridge sites) indicate that the area of the repository that would be affected by contact metamorphism is minimal, being limited to less than 10 meters away from dike contacts (Valentine et al. 1998, p. 5-41). Because the repository block will not be significantly affected, metamorphism does not provide a mechanism to affect dose within the repository performance period (10,000 years). Therefore, the Primary and Secondary FEPs are *Excluded* from the TSPA–SR based on low consequence to dose.

TSPA Disposition: "Metamorphism" is *Excluded* from the TSPA–SR as described under the Screening Argument.

Supplemental Discussion: See also "Tectonic activity–large scale" (1.2.01.01.00) and "Igneous activity causes changes to rock properties" (1.2.04.02.00) for a more complete discussion on tectonic processes and effects of igneous intrusions

Related PMRs, AMRs, and Calculations: *Features, Events, and Processes: Disruptive Events* ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
SDS1: Faults
SDS4: Tectonic activity

Integrated Subissues/Related Subissues

ENG1 Eng: Degradation of Engineered Barriers / ENFE2, CLST1, CLST2, CLST6, RDTME3
ENG2 Eng: Mechanic Disruption of Engineered Barriers / CLST1, CLST2, CLST6 RDTME2, RDTME3
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, SDS2, SDS3, SDS4
UZ2 Geo: Flow Paths in UZ / USFIC4, SDS3, SDS4
SZ1 Geo: Flow Paths in SZ / USFIC4, USFIC5, SDS3, SDS4

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Tectonic activity–large scale (1.2.01.01.00)
Faulting (1.2.02.02.00)
Diagenesis (1.2.08.00.00)
Effects of subsidence (2.2.06.04.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Igneous activity causes changes to rock properties (1.2.04.02.00)
Change in stress (due to thermal, seismic, or tectonic effects) change the porosity and permeability of rock (2.2.06.01.00)
Geochemical interactions in geosphere (dissolution, precipitation, weathering) and effects on radionuclide transport (2.2.08.03.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Metamorphic activity (1.2.05.00.01)

Relationship to Primary FEP: No description in source document, retained in FEPs list for completeness
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

<u>*Secondary FEP Name and Number:*</u> Regional metamorphism (1.2.05.00.02)

Relationship to Primary FEP: Specific to sites in England, but applicable due to the consideration of regional metamorphic effects.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

<u>*Secondary FEP Name and Number:*</u> Metamorphic activity (1.2.05.00.03)

Relationship to Primary FEP: Definition of metamorphic activity as used for WIPP site and, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

<u>*Secondary FEP Name and Number:*</u> Metamorphic activity (1.2.05.00.04)

Relationship to Primary FEP: Provides list of possible change mechanisms resulting from metamorphism. Most of these are addressed in the *Features, Events, Processes: Disruptive Events* ANL-WIS-MD-000005(CRWMS M&O 2000f) and were shown to be of low consequence to dose.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

6.2.14 Diagenesis (1.2.08.00.00)

FEP Description: This category contains FEPs related to natural processes that alter the mineralogy or other properties of rocks after the rocks have formed under temperature- and pressure-conditions normal to the upper few kilometers of the earth's crust. Diagenesis includes chemical, physical, and biological processes that take place in rocks after formation but before eventual metamorphism or weathering. This FEP is assumed to refer to natural diagenetic processes only.

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

Screening Argument: Diagenetic changes (such as compaction and cementation) of surface deposits have the potential to influence rates of infiltration in the shallow vadose zone. These diagenetic processes tend to decrease porosity and/or permeability and result in decreased rather than increased rates of infiltration. Decreases in infiltration would generally be beneficial to repository performance by limiting the amount of water seeping into the emplacement drifts and thereby lessening the potential for radionuclide transport through the unsaturated zone below the repository. Regardless, the effect of variability in rates and location of infiltration are already addressed in the TSPA–SR by varying infiltration rates associated with varying climatic conditions.

Additionally, diagenetic processes in the vadose zone occur sufficiently slowly (i.e., on the order of several thousand years based on Humphrey et al. 1986, pp. 77 and 78) that natural mineralogical changes (as opposed to repository-induced changes) that may occur during the period of regulatory interest (10,000 years) can be *Excluded* from the TSPA–SR based on low consequence to dose. The products of past diagenesis in the host rocks are included implicitly in the TSPA–SR through the assignment of models and parameters for flow and transport in the SZ and UZ.

TSPA Disposition: "Diagenesis" is *Excluded* from the TSPA–SR as described under the Screening Argument.

Supplemental Discussion: See Attachment IIA for a more detailed discussion of diagenetic processes. From the discussion in Attachment IIA, it is concluded that the effects of diagenesis on the Yucca Mountain project are of low consequence to dose for the following reasons:

1) Increased diagenetic effects on sub-surface rock properties are usually associated with the heat and temperatures associated with deep burial (inferred from Palmer and Barton 1987, p. 39; and from Krystinik 1990, p. 8-3). The geologic setting of Yucca Mountain, however, is one of minimal rates of subsidence (see Section 6.2.13 "Metamorphism" (1.2.05.00.00) of this document (ANL-WIS-MD-000019) for discussion of subsidence rates). Consequently, deep burial is not a credible diagenetic mechanism at Yucca Mountain within the repository performance period (10,000 years).

2) The primary near-surface diagenetic processes of concern are compaction and cementation. Compaction is not of significant concern following initial reduction in porosity coincident with redeposition because "compaction does not generally become an important factor in diagenesis until the onset of grain deformation and pressure solution during deeper burial

diagenesis." (Krystinik. 1990, p. 8-3). Cementation, when and where it does occur, generally decreases the vertical infiltration rate (Reeves 1976, p. 110). Although cementation of calcium carbonate can be completed with a few thousand years, the studies by Lattman (1973, p. 3015) suggest that cementation by calcium carbonate is not a significant process in rhyolitic tuffs due to the lack of carbonate source material. Some cementation may occur if carbonate materials are present in the regional terrane to provide a source material. What cementation does exist is not widespread and is very limited. Other cements may develop, as documented by Krystinik (1990, p. 8-4), but the cementation process is reversible (Krystinik 1990, p. 8-3).

3) Climate change will affect the rate and location of shallow diagenesis due to changes in temperature, precipitation, vegetation, and other less critical factors that control the rate and distribution of diagenetic changes. The net effect, however, will be to vary the depth of the cemented horizons (due to dissolution/reprecipitation), change the composition of the cement materials (due to differing equilibrium conditions), and otherwise drive the diagenetic processes to differing endpoints and redistribute the areas affected, rather than eliminating the net effects of diagenesis. The effect of variability in rates and location of infiltration is already addressed by varying infiltration rates associated with varying climatic conditions.

4) The time required for complete diagenesis in the shallow environment (extending from the surface to the downward limit of evapotranspiration) is potentially within the timescale of concern for the repository performance assessment (i.e., 10,000 years, see Lattman and Simonberg 1971, p. 277; Krystinik 1990, p. 8-1; Humphrey et al. 1986, p 77 and 78). The net effects of shallow diagenesis, however, stabilize the surface environment and decrease the net vertical infiltration rate (Reeves 1976, p. 110). Completion of diagenesis in the deeper vadose zone (base of the shallow zone to the top of the saturated zone), however, is likely to occur over periods longer than the timescale of concern.

Changes induced by the repository are likely to be of much greater consequence at the repository depth than naturally occurring diagenetic changes. Repository-induced changes (e.g., geochemical and thermal factors), are addressed by other FEPs listed in the *YMP FEP Database* (CRWMS M&O 2000d, Appendix D). See FEPs under sub-headings 2.2.08 (Geochemical processes and conditions) and 2.2.10 (Thermal processes and conditions).

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

<u>*Integrated Subissues/Related Subissues*</u>

ENG1 Eng: Degradation of Engineered Barriers / ENFE1, ENFE2, CLST1, CLST2, CLST6, RDTME3
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, SDS2, SDS3, SDS4
UZ2 Geo: Flow Paths in UZ / USFIC4, SDS3, SDS4
SZ1 Geo: Flow Paths in SZ / USFIC4, USFIC5, SDS3, SDS4

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Metamorphism (1.2.05.00.00)
Erosion/denudation (1.2.07.01.00)
Deposition (1.2.07.02.00)
Climate change, global (1.3.01.00.00)
Climate modification increases recharge (1.4.01.01.00)
Effects of subsidence (2.2.06.04.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Change in stress (due to thermal, seismic, or tectonic effects) changes the porosity and permeability of rock (2.2.06.01.00)
Geochemical interactions in geosphere (dissolution, precipitation, weathering) and effects on radionuclide transport (2.2.08.03.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Diagenesis (1.2.08.00.01)

Relationship to Primary FEP: Description distinguishes diagenesis from metamorphism and weathering, and is the basis of Primary FEP.
Screening and Disposition: Excluded from the TSPA–SR—Low consequence to dose

<u>*Secondary FEP Name and Number:*</u> Diagenesis (1.2.08.00.02)

Relationship to Primary FEP: Specific processes described. Deals with shallow burial, which is distinct from metamorphism. It is, therefore, addressed in this Primary FEP.
Screening and Disposition: Excluded from the TSPA–SR—Low consequence to dose

<u>*Secondary FEP Name and Number:*</u> Fracture infills (1.2.08.00.03)

Relationship to Primary FEP: Addresses fracture infills due to mineralization. This is not a metamorphic process, and is, therefore, included in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

<u>*Secondary FEP Name and Number:*</u> Diagenesis (1.2.08.00.04)

Relationship to Primary FEP: No description in source document, retained in FEPs list for completeness
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

6.2.15 Salt Diapirism and Dissolution (1.2.09.00.00)

FEP Description: This category contains FEPs related to geologic processes primarily relevant to repositories located in salt and evaporite deposits. Diapirism refers to the tendency of any rock, but most particularly salt, to flow under lithostatic loading when density and viscosity contrasts with surrounding strata are favorable. Salt domes are the best-known example of salt diapirism. Dissolution can occur when any soluble mineral is removed by flowing water, and large-scale dissolution is a potentially important process in rocks that are composed predominantly of water-soluble evaporite minerals, such as salt.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—By Regulation and Low consequence to dose

Screening Argument: "Salt Diapirism and dissolution" is *Excluded* from the TSPA–SR based on regulation. Evaporite deposits of sufficient volume to develop a diapir or to be of concern for dissolution have not been reported near Yucca Mountain. Evaluation of this FEP would, therefore, be inconsistent with the guidance at proposed rule 10 CFR §63.115(a)(1) (64 FR 8640), which specifies that "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," and at proposed rule 10 CFR §63.115(a)(4) (64 FR 8640), which specifies that "Evolution of the geologic setting shall be consistent with present knowledge of natural processes." It would also be outside the scope and intent stated at proposed rule 10 CFR §63.21(c)(1) (64 FR 8640), which specifies consideration and description of "features, events, and processes outside of the site to the extent the information is relevant and material to safety or performance of the geologic repository."

Because voluminous evaporite deposits do not exist in the vicinity of Yucca Mountain and the repository is not planned for a salt dome or cavern, "Salt diapirism and dissolution" is *Excluded* from the TSPA–SR based on the regulatory specification to evaluate only relevant site features, events, and processes. The lack of evaporite deposits at Yucca Mountain also renders this FEP of low consequence to dose.

TSPA Disposition: "Salt diapirism and dissolution" is *Excluded* from the TSPA–SR as described under the Screening Argument

Supplemental Discussion: See Screening Argument

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>*Directly Affected Subissues*</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening

<u>*Integrated Subissues/Related Subissues*</u>

None

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Metamorphism (1.2.05.00.00)
Diapirism (1.2.09.01.00)
Effects of subsidence (2.2.06.04.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Salt creep (2.2.06.05.00)
Large scale dissolution (1.2.09.02.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.2.16 Diapirism (1.2.09.01.00)

FEP Description: The process by which plastic, low density rocks (most commonly evaporites) may flow under lithostatic loading when density and viscosity contrasts with surrounding strata are favorable. Such a process would modify the groundwater flow regime and affect radionuclide transport.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—By Regulation (for salt diapirism) and Low consequence to dose (for igneous diapirism)

Screening Argument: "Diapirism" is *Excluded* from the TSPA–SR based on proposed regulatory requirements (64 FR 8640, §63.115(a)(1 and 4)) and low consequence to dose.

In the broadest sense, diapirism encompasses "the piercing or rupturing of domed or uplifted rocks by mobile core material, by tectonic stresses as in anticlinal folds, by the effect of geostatic load in sedimentary strata as in salt domes or shale diapirs, or by igneous intrusions, forming diapiric structures such as plugs." (Bates and Jackson 1984, p. 138).

There is no past evidence of diapirism within the geologic setting at Yucca Mountain. Current tectonic stresses in the region are extensional, and an extensional stress regime is not conducive to anticlinal folding and doming, although it may be conducive to igneous activity. The geologic materials at Yucca Mountain are brittle (particularly the welded tuffs) and require high temperatures and pressures in order to achieve ductile formation. The failure mechanism is, therefore, generally by fracturing and faulting. The volcanic rocks present at the site are not capable of ductile flow under the stresses and at the temperatures expected to result at the site due to geostatic loading.

The concept of diapirism is usually applied to salt structures resulting from geostatic loading. Salt Diapirism is addressed in Section 6.2.15 of this document (ANL-WIS-MD-000019) and is *Excluded* from the TSPA–SR based on regulatory considerations that direct the DOE to evaluate only relevant site features, events, and processes, and are it, therefore, also of low consequence to dose. Hence, further consideration of diapirism related to tectonic stresses and geostatic loading is precluded at proposed rule 10 CFR 63 (64 FR 8640, §63.21(c)(1); §63.115(a)(1 and 4)) because the necessary geologic materials and stress environment do not occur at Yucca Mountain.

Diapirism related to igneous intrusion is relevant to the disruptive scenario for igneous intrusion. Smith et al. (1998, p. 155) point out that extension is accommodated in the upper crust by dike intrusion of vertical dikes perpendicular to the extension direction, with surface deformation possibly including open fissures, monoclines, normal faults, and graben, and with surface uplift being approximately a few meters (Smith et al. 1998, Fig. 2). The potential for hydrologic response to igneous activity is more fully evaluated in the FEP "Hydrologic response to igneous activity" (1.2.10.02.00) (CRWMS M&O 2000d, Appendix D, and CRWMS M&O 2000f, Section 6.2.16) and is *Excluded* from the TSPA–SR based on low consequence to dose. In short, igneous activity is most likely to be in the form of dikes oriented subparallel to the direction of existing groundwater flow and faults and fractures (and, therefore, of minimal impact on ground water flow systems), as opposed to significant vertical changes due to uplift or doming events related to igneous-induced diapirism.

TSPA Disposition: "Diapirism" is *Excluded* from the TSPA–SR as described under the Screening Argument.

Supplemental Discussion: See Screening Argument

Related PMRs, AMRs, and Calculations: *Features, Events, and Processes: Disruptive Events* ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening

Integrated Subissues/Related Subissues

ENG2 Eng: Mechanical Disruption of Engineered Barriers / IA2
Direct1 Geo: Volcanic Disruption of Waste Packages / IA1

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Igneous intrusion into repository (1.2.04.03.00)
Salt creep (2.2.06.05.00)

Links to FEPs that examine similar consequences and effects:

Hydrologic response to igneous activity (1.2.10.02.00)
Igneous activity causes changes to rock properties (1.04.02.00.00)
Salt diapirism and dissolution (1.2.09.00.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Diapirism (1.2.09.01.01)

Relationship to Primary FEP: No description in source document, retained in FEPs list for completeness.
Screening and Disposition: Excluded from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Salt deformation (1.2.09.01.02)

Relationship to Primary FEP: Description is particular to the WIPP site, which is in a different geologic setting that includes bedded evaporite deposits.
Screening and Disposition: Excluded from the TSPA–SR—By Regulation

<u>Secondary FEP Name and Number:</u> Diapirism (1.2.09.01.03)

Relationship to Primary FEP: Description is particular to the WIPP site, but description provides several salt deformation mechanisms.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

6.2.17 Deliberate Human Intrusion (1.4.02.01.00)

FEP Description: Humans could deliberately intrude into the repository. Without appropriate precautions, intruders could experience high radiation exposures. Moreover, containment may be left damaged, which could increase radionuclide release rates to the biosphere. Motivation for deliberate human intrusion includes mining, waste retrieval, site remediation/improvement, archaeology, sabotage, and acts of war.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—By Regulation (for Deliberate Intrusion)

Included in the TSPA–SR—Does not satisfy a screening criterion (for a stylized human- intrusion scenario)

Screening Argument: "Deliberate human intrusion", including all Secondary FEPs is *Excluded* from the TSPA–SR human intrusion scenario based on regulation. Consistent with regulatory specifications, the only mechanism of intrusion to be considered in the human-intrusion scenario is intersection (or penetration) of the repository by a single borehole (proposed rule 10 CFR 63: 64 FR 8640, §63.113(d) and proposed rule 40 CFR 197: 64 FR 46976, §197.26 (a - f)). Neither of the regulations directly addresses the issue of inadvertent versus deliberate intrusion.

At proposed rule 10 CFR 63 (64 FR 8640, Section XI. Human Intrusion), the supplemental text provides a description of the NRC's considerations in the use of a stylized human-intrusion scenario. These considerations provide that:

> The Commission does not intend to speculate on the virtual infinity of human intrusion scenarios that could be contemplated, nor does it intend for this analysis to address the full range of possible intrusions that could occur.

This statement implies that the NRC is not primarily concerned with addressing the motivation or range of specific methodologies that might be involved in a human-intrusion scenario, but rather "intends that this analysis show that the repository exhibits some resilience to a breach of engineered and geologic barriers from events that are reasonably of concern." The NRC then proposes that the DOE use "current practices for resource exploration to establish properties for the intrusion scenario," and then specifies the type of intrusion to be considered at proposed rule 10 CFR 63 (64 FR 8640, §63.113(d)).

The supplemental text also specifies that:

> Hazards to the intruders themselves (drillers, miners, etc.) ... from material brought to the surface by the assumed intrusion should not be included in this analysis, according to the NAS.

At proposed rule 40 CFR 197 (64 FR 46976, Section III.E. What Is the Standard for Human Intrusion?), a deliberate intrusion is explicitly excluded. The bases for the EPA's guidance is provided in the supplemental discussion section below.

Therefore, "Deliberate intrusion" is considered by the TSPA as *Excluded* from the TSPA–SR due to the constraint that a stylized intrusion be analyzed as directed by regulations for the human-intrusion scenario. Consistent with proposed regulatory requirement (64 FR 8640, §63.113(d)), the only human intrusion action that must be analyzed is a stylized drilling

TSPA Disposition: The specifications for the human-intrusion scenario are listed at proposed rule 40 CFR §197.25 and §197.26 (64 FR 46976) and proposed rule 10 CFR §63.113(d) (64 FR 8640), and are addressed in the TSPA–SR.

Supplemental Discussion: The supplemental text to the proposed rules does provide some guidance regarding inadvertent versus deliberate intrusions. With regard to the National Academy of Sciences' (NAS) conclusion that " . . . it makes no sense...to try to protect against the risks arising from the conscious activities of future human societies," (64 FR 46976, Section III E), the EPA explicitly states in 64 FR 46976, (Section III.E. What Is the Standard for Human Intrusion?), that:

> We agree with this conclusion and propose to find it acceptable to exclude long-term or deliberate, as opposed to acute and inadvertent, human disturbance of the disposal system from the human intrusion analysis on the theory that society could retain at least some general knowledge of the disposal system and, therefore, would know that such actions could be dangerous. The proposed human-intrusion scenario, therefore, includes only an acute inadvertent intrusion.

Hypothetical situations in which future intruders are aware of the repository but are unaware of the risks that it poses (Assumption 5.4 of this document, ANL-WIS-MD-000019) are considered to be a form of inadvertent intrusion, and are *Included* in the TSPA–SR as specified by proposed regulatory requirements (see Section 6.2.18 of this document (ANL-WIS-MD-000019) "Inadvertent human intrusion" (1.4.02.02.00)). In contrast, sabotage, acts of war, archeological investigation of the repository, mining, or reentry of the repository to retrieve waste after closure or for site improvement are encompassed within the definition of deliberate intrusion and are, therefore, *Excluded* from consideration in the TSPA.

Extensive review of the potential for occurrences of natural resources at Yucca Mountain has concluded that no currently economic resources occur at the site, nor are any likely to be found in the future (DOE 1998, Section 2.2.7.3). Consequently, Yucca Mountain is not a desirable target area for drilling associated with natural resource exploration or exploitation

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME3: Underground Facility Design and Performance

Integrated Subissues/Related Subissues

ENG2 Eng: Mechanical Disruption of Engineered Barriers: CLST2, CLST6

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Records and markers, repository (1.1.05.00.00)
Administrative control, repository site (1.1.10.00.00)
Inadvertent human intrusion (1.4.02.02.00)
Unintrusive site investigation (1.4.03.00.00)
Social and institutional developments (1.4.08.00.00)
Urban and industrial land and water use (2.4.10.00.00)

Links to FEPs that examine similar consequences and effects:

Drilling activities (human intrusion) (1.4.04.00.00)
Effects of drilling intrusion (1.4.04.01.00)
Mining and other underground activities (1.4.05.00.00)
Explosions and crashes (1.4.11.00.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Chemical sabotage (1.4.02.01.01)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Waste retrieval, mining (1.4.02.01.02)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Archeological intrusion (1.4.02.01.03)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Recovery of repository materials (1.4.02.01.04)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Malicious intrusion (1.4.02.01.05)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR-By Regulation

<u>*Secondary FEP Name and Number:*</u> Archaeological investigation (1.4.02.01.06)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Deliberate intrusion (1.4.02.01.07)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Malicious intrusion (1.4.02.01.08)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Deliberate drilling intrusion (1.4.02.01.09)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Archeological investigations (1.4.02.01.10)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Post-closure surface activities (intrusion) (1.4.02.01.11)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Intrusion into accumulation zone in biosphere (1.4.02.01.12)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Unsuccessful attempt at site improvement (1.4.02.01.13)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Sabotage (1.4.02.01.14)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Sabotage (1.4.02.01.15)

Relationship to Primary FEP: A particular form of deliberate human intrusion
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Sudden energy release (in waste and EBS) (1.4.02.01.16)

Relationship to Primary FEP: A particular form of deliberate human intrusion. The description indicates that the energy release is due to sabotage, which is a form of deliberate human intrusion.
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Other future uses of crystalline rock (1.4.02.01.17)

Relationship to Primary FEP: This relates through the an assumption of mining of the crystalline material. Mining is a particular form of deliberate human intrusion.
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Intrusion (human) (1.4.02.01.18)

Relationship to Primary FEP: A generic description pertaining to resource recovery. Because it would be purposed, it is considered as deliberate human intrusion.
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

6.2.18 Inadvertent Human Intrusion (1.4.02.02.00)

FEP Description: Humans could accidentally intrude into the repository. Without appropriate precautions, intruders could experience high radiation exposures. Moreover, containment may be left damaged, which could increase radionuclide release rates to the biosphere. Inadvertent human intrusion might occur during scientific, mineral or geothermal exploration.

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

Screening Argument: "Inadvertent human intrusion" and the Secondary FEPs are *Included* in the TSPA–SR in the human-intrusion scenario as described under TSPA Disposition.

TSPA Disposition: In accordance with regulatory specifications at proposed rule 40 CFR §197.25 and §197.26 (64 FR 46976) and proposed rule 10 CFR §63.113(d) (64 FR 8640). "Inadvertent human intrusion" and the Secondary FEP "Accidental intrusion" are *Included* in the TSPA–SR through the human-intrusion scenario.

At proposed rule 40 CFR 197 (64 FR 46976, Section III.E. What Is the Standard for Human Intrusion?), the supplemental text explicitly states that, "the proposed human-intrusion scenario, therefore, includes only an acute inadvertent intrusion." This scenario is specified as a stylized scenario to address all forms of inadvertent human intrusion.

In accordance with proposed rule 10 CFR §63.113(d) (64 FR 8640), doses from the drilling intrusion are estimated only for the long-term subsurface release pathways involving a damaged container and an inadequately sealed borehole. The dose resulting from the subsurface pathway will be calculated for the critical group as defined at proposed rule 10 CFR §63.115(b) (64 FR 8640). Supplemental text at proposed rule 10 CFR 63 (64 FR 8640, Section XI. Human Intrusion) specifically excludes consideration of hazards to the intruders or hazards to the public from material brought to the surface.

The analysis for human intrusion in the TSPA–SR is presented in *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-00001 REV 00 (CRWMS M&O 2000c, Section 4.4).

Related FEPs are discussed in Section 6.2.20 and 6.2.21

Supplemental Discussion: At proposed rule 40 CFR 197 (64 FR 46976, Section III.E. What Is the Standard for Human Intrusion?), the supplemental text is explicit with regard to excluding a specific deliberate intrusion. With regard to NAS's conclusion that "it makes no sense...to try to protect against risk from the conscious activities of future human societies," the EPA states that, "... The proposed human-intrusion scenario, therefore, includes only an acute, inadvertent intrusion."

Hypothetical situations in which future intruders are aware of the repository but are unaware of the risks that it poses (Assumption 5.4 of this document, ANL-WIS-MD-000019) are considered to be a form of inadvertent intrusion, and are *Included* in the TSPA–SR as specified by proposed regulatory requirements. Consistent with guidance and proposed regulatory specifications listed above, the only human-intrusion scenario that must be *Included* in TSPA is a stylized drilling intrusion.

At proposed rule10 CFR 63 (64 FR 8640, Section XI. Human Intrusion), the NRC indicates that ". . . human intrusion be excluded from the performance assessment, but that the consequences of an assumed human intrusion scenario should be calculated to determine if repository performance would be substantially degraded as a result of the intrusion." This approach is reflected at proposed rule 10 CFR §63.113(d) (64 FR 8640), which specifies that the ability of the geologic repository to limit radiological exposures in the event of limited human intrusion into the engineered barrier system ". . . shall be demonstrated through a separate performance assessment that meets the requirements specified at §63.114 and uses the reference biosphere and critical group specified at §63.115." A similar approach is also specified by the EPA at proposed rule 40 CFR 197 (64 FR 46976, Section III.C.1 What Limits Are there on Factors Included in the Performance Assessment?). Section III.C.1. specifies that:

> The human intrusion analysis would require a separate assessment of the effects of human intrusion upon the resilience of the Yucca Mountain disposal system. Following the recommendation of the NAS, we intend the analysis to be an assessment of the disposal system's isolation capability following a single, stylized human intrusion. The analysis required to determine compliance with the ground water protection standards applies only to undisturbed performance.

Related PMRs, AMRs, and Calculations: *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-00001 REV 00 (CRWMS M&O 2000c) None

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME3: Underground Facility Design and Performance

<u>Integrated Subissues/Related Subissues</u>

ENG2 Eng: Mechanical Disruption of Engineered Barriers: CLST2, CLST6

Related Primary FEPs:

<u>Links to FEPs that examine related, but distinct, consequences and effects</u>:

Records and markers, repository (1.1.05.00.00)
Administrative control, repository site (1.1.10.00.00)
Unintrusive site investigation (1.4.03.00.00)
Social and institutional developments (1.4.08.00.00)
Explosions and crashes (1.4.11.00.00)
Urban and industrial land and water use (2.4.10.00.00)

<u>*Links to FEPs that examine similar consequences and effects:*</u>

Deliberate human intrusion (1.4.02.01.00)
Drilling activities (human intrusion) (1.4.04.00.00)
Effects of drilling intrusion (1.4.04.01.00)
Mining and other underground activities (1.4.05.00.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Accidental intrusion (1.4.02.02.01)

Relationship to Primary FEP: Redundant with Primary FEP description, suggests that outcome of various intrusion modes is similar, which suggests use of a stylized scenario may be appropriate

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

6.2.19 Unintrusive Site Investigation (1.4.03.00.00)

FEP Description: This category contains FEPs related to airborne, geophysical, or other surface-based investigations of a repository site after its closure.

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

Screening Argument: "Unintrusive site investigation" is *Excluded* from the TSPA–SR based on low consequence to dose. By definition, unintrusive activities will have no discernible effect on the performance of the system.

Proposed rule 40 CFR §197.12 (64 FR 46976) defines human intrusion as "...breaching of any portion of the Yucca Mountain Disposal system by human activity." The Yucca Mountain disposal system is defined as "the combination of underground engineered and natural barriers at the Yucca Mountain site, which prevents or substantially reduces releases from the disposed radioactive material." Consequently, any human activity (including site investigations) or human-induced activity which has a significant negative impact on the barrier system is, by definition, human intrusion. Proposed rule 40 CFR §197.26 (64 FR 46976) and proposed rule 10 CFR §63.113(d) (64 FR 8640) clearly stipulate that human intrusion shall be considered only through the specified stylized-drilling scenario.

TSPA Disposition: "Unintrusive site investigation" is *Excluded* from the TSPA–SR as described under the Screening Argument

Supplemental Discussion: See Screening Argument

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

Integrated Subissues/Related Subissues

ENG2 Eng: Mechanical Disruption of Engineered Barriers: CLST2, CLST6

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Records and markers, repository (1.1.05.00.00)
Administrative control, repository site (1.1.10.00.00)
Social and institutional developments (1.4.08.00.00)
Deliberate human intrusion (1.4.02.01.00)
Inadvertent human intrusion (1.4.02.02.00)
Drilling activities (human intrusion) (1.4.04.00.00)
Explosions and crashes (1.4.11.00.00)

Links to FEPs that examine similar consequences and effects:

Urban and industrial land and water use (2.4.10.00.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.2.20 Drilling Activities (Human Intrusion) (1.4.04.00.00)

FEP Description: This category contains FEPs related to any type of drilling activity in the repository environment. These may be taken with or without knowledge of the repository. Drilling activities may be associated with natural resource exploration (water, oil and gas, minerals, geothermal energy), waste disposal (liquid), fluid storage (hydrocarbon, gas), or reopening existing boreholes.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion (for a stylized drilling scenario)

Excluded from the TSPA–SR—By Regulation
(for specific types of drilling scenarios as presented in the secondary FEPs)

Screening Argument: The Secondary FEPs include multiple drilling methods and resource exploration and exploitation scenarios. Proposed rule 40 CFR §197.26 (64 FR 46976), and proposed rule 10 CFR §63.113(d) (64 FR 8640) clearly stipulate that human intrusion shall be considered only through the specified stylized drilling scenario. The proposed EPA regulations assume a human-intrusion scenario based on drilling for groundwater exploration (see criteria listed in Section 4.2.2.5). The Secondary FEPs are, therefore, *Excluded* from the TSPA–SR and from the human-intrusion scenario. However, because of the similarities in equipment and techniques, the regulatory specified stylized drilling scenario is essentially equivalent to the methods and techniques listed for the Secondary FEPs, which include drilling for natural resources (including water, oil and gas, minerals, geothermal energy), drilling for waste disposal, drilling for fluid storage, and for reopening of existing boreholes.

TSPA Disposition: "Drilling activities (human intrusion)" is *Included* in the TSPA–SR in the human-intrusion scenario. The specifications for the human-intrusion scenario are listed at proposed rule 40 CFR 197 (64 FR 46976, §197.26 (a - f)) and at proposed rule 10 CFR 63 (64 FR 8640, §63.113(d)). Consistent with proposed regulatory considerations (as addressed at proposed rule 10 CFR 63 (64 FR 8640, Section XI. Human Intrusion) and proposed rule 40 CFR 197 (64 FR 46976, Section III.E. What Is the Standard for Human Intrusion?), inadvertent human intrusion by drilling is the only form of human intrusion considered in the human-intrusion scenario.

The analysis for human intrusion in the TSPA–SR is presented in *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-00001 REV 00 (CRWMS M&O 2000c, Section 4.4).

Supplemental Discussion: The events associated with drilling intrusion that must be considered in the human-intrusion scenario are specified in the proposed regulations. Many events associated with specific types of intrusion (see Secondary FEPs) are also *Excluded* from the TSPA. Particularly, at proposed rule 10 CFR 63 (64 FR 8640, Section XI. Human Intrusion), the supplemental text provides description of the NRC's considerations in the use of a stylized human-intrusion scenario. These considerations include the statement that: "Hazards... to the public from material brought to the surface by the assumed intrusion should not be included in this analysis, according to the NAS." The DOE Interim Guidance (Dyer 1999, Section 113(d)) specifies that "It shall be assumed that the effect of the drilling is no more severe than the creation of an enhanced groundwater flow path from the crest of Yucca Mountain through a waste package to the water table. That is, the drilling process itself would not force wastes down to the saturated zone", which is similar to discussions at proposed 40 CFR 197 (Section III.E. What Is the Standard for Human Intrusion?). Thus, events associated with the pumping of fluids into or out of the borehole (such as might occur during water or hydrocarbon recovery, or during waste disposal) are *Excluded* from the TSPA–SR based on regulatory specifications or considerations.

Extensive review of the potential for occurrences of natural resources at Yucca Mountain has concluded that no currently economic resources occur at the site, nor are any likely to be found in the future (DOE 1998, Section 2.2.7.3). Consequently, Yucca Mountain is not a desirable target area for drilling associated with natural resource exploration or exploitation.

Related PMRs, AMRs, and Calculations: *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-00001 REV 00 (CRWMS M&O 2000c)

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

Integrated Subissues/Related Subissues

ENG2 Eng: Mechanical Disruption of Engineered Barriers: CLST2, CLST6

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Records and markers, repository (1.1.05.00.00)
Administrative control, repository site (1.1.10.00.00)
Social and institutional developments (1.4.08.00.00)
Urban and industrial land and water use (2.4.10.00.00)

Links to FEPs that examine similar consequences and effects:

Open site investigation boreholes (1.1.01.01.00)
Loss of integrity of borehole seals (1.1.01.02.00)
Deliberate human intrusion (1.4.02.01.00)
Inadvertent human intrusion (1.4.02.02.00)
Effects of drilling intrusion (1.4.04.01.00)
Abandoned and undetected boreholes (1.4.04.02.00)
Mining and other underground activities (1.4.05.00.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Geothermal (1.4.04.00.01)

Relationship to Primary FEP: Specific to WIPP. This is a particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Other resources (1.4.04.00.02)

Relationship to Primary FEP: Specific to WIPP. This is a particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Enhanced oil and gas recovery (1.4.04.00.03)

Relationship to Primary FEP: Specific to WIPP. This is a particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Liquid waste disposal (1.4.04.00.04)

Relationship to Primary FEP: Specific to WIPP. This pertains particular to drilling for waste disposal and is, therefore, addressed by the Primary FEP
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Hydrocarbon storage (1.4.04.00.05)

Relationship to Primary FEP: Pertains to fluid storage, which generally involves storage and retrieval through wells and is, therefore, addressed in this Primary FEP
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Exploratory drilling for hydrocarbons (1.4.04.00.06)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Exploratory drilling for metals (1.4.04.00.07)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Boreholes – exploration (1.4.04.00.08)

Relationship to Primary FEP: Description is inferred to pertain to a generic drilling scenario related to resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Injection of liquid waste (1.4.04.00.09)

Relationship to Primary FEP: No description in source document. It is inferred to pertain to waste disposal by well injection and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Exploratory drilling (1.4.04.00.10)

Relationship to Primary FEP: No description in source document. It is inferred to pertain to natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Exploitation drilling (1.4.04.00.11)

Relationship to Primary FEP: No description in source document. It is inferred to pertain to a particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Exploratory drilling (1.4.04.00.12)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Geothermal exploitation (1.4.04.00.13)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Liquid waste injection (1.4.04.00.14)

Relationship to Primary FEP: Pertains particularly to waste disposal by well injection and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Oil and gas exploration (1.4.04.00.15)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Potash exploration (1.4.04.00.16)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Water resource exploration (1.4.04.00.17)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Oil and gas exploration (1.4.04.00.18)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Groundwater exploitation (1.4.04.00.19)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Geothermal energy production (1.4.04.00.20)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Geothermal energy production (1.4.04.00.21)

Relationship to Primary FEP: No description in source document. It is inferred to pertain to a particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Borehole – well (1.4.04.00.22)

Relationship to Primary FEP: Concerns reuse/rentry of existing boreholes as a water well and is, therefore, address by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Reuse of boreholes (1.4.04.00.23)

Relationship to Primary FEP: Concerns reuse/rentry of existing boreholes and is, therefore, address by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Oil and Gas extraction (1.4.04.00.24)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Liquid waste disposal (1.4.04.00.25)

Relationship to Primary FEP: Pertains particularly to oil-and-gas waste disposal by well injection and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Enhanced oil and gas production (1.4.04.00.26)

Relationship to Primary FEP: A particular type of natural resource exploration and is, therefore, addressed by the Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Hydrocarbon storage (1.4.04.00.27)

Relationship to Primary FEP: Pertains to fluid storage, which generally involves storage and retrieval through wells and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

6.2.21 Effects of Drilling Intrusion (1.4.04.01.00)

FEP Description: Drilling activities that intrude into the repository may create new release pathways to the biosphere and alter existing pathways. Possible effects of a drilling intrusion include interaction with waste containers, increased saturation in repository leading to enhanced transport to the SZ, changes to groundwater and EBS chemistry, and waste brought to surface.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion (for interactions and changes in condition)

Excluded from the TSPA–SR—By Regulation (for materials brought to the surface)

Screening Argument: The supplemental text for proposed rule 10 CFR 63 (64 FR 8640, Section XI. Human Intrusion) directs that the assessment not include "hazards to the intruders themselves (drillers, miners, etc.) or to the public from material brought to the surface by the assumed intrusion ... ." Consequently, Secondary FEPs dealing with materials brought to the surface are *Excluded* from the TSPA–SR. This includes four of the Secondary FEPs, including "Direct exposure to waste in mud pit" (1.4.04.01.03), "Cuttings" (1.4.04.01.10), Cavings (1.4.04.01.11), and Spallings (1.4.04.01.12).

TSPA Disposition: In accordance with regulatory specifications at proposed rule 40 CFR 197 (64 FR 46976, §197.26(a - f)) and proposed rule 10 CFR 63 (64 FR 8640, §63.113(d)), inadvertent human intrusion is *Included* in the TSPA–SR by estimating the consequences of the penetration of the repository by a borehole in the human-intrusion scenario. Consistent with that approach, all Secondary FEPs for "Effects of drilling intrusion are considered as *Included* in the TSPA–SR, with the exception of those previously listed that deal with materials brought to the surface.

Proposed rule 40 CFR §197.26(a - f) (64 FR 46976) specifies the presumption of a single borehole through a degraded waste package, and that the borehole is not carefully sealed. The evaluation is also limited by regulation to the release of radionuclides that occur as a result of the intrusion and that are transported through the resulting borehole to the saturated zone. Proposed rule 10 CFR §63.113(d) (64 FR 8640) specifies that intrusion occurs 100 years after permanent closure.

The analysis for human intrusion in the TSPA–SR is presented in *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-00001 REV 00 (CRWMS M&O 2000c, Section 4.4).

Supplemental Discussion: See Screening Argument

Related PMRs, AMRs, and Calculations: *Total System Performance Assessment for the Site Recommendation* TDR-WIS-PA-00001 REV 00 (CRWMS M&O 2000c)

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening

TSPAI 3: Model Abstraction / Data Use and Validity

Integrated Subissues/Related Subissues

ENG2 Eng: Mechanical Disruption of Engineered Barriers: CLST2, CLST6

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Unintrusive site investigation (1.4.03.00.00)
Mining and other underground activities (1.4.05.00.00)
Deliberate human intrusion (1.4.02.01.00)
Inadvertent human intrusion (1.4.02.02.00)

Links to FEPs that examine similar consequences and effects:

Open site investigation boreholes (1.1.01.01.00)
Loss of integrity of borehole seals (1.1.01.02.00)
Effects of drilling intrusion (1.4.04.01.00)
Abandoned and undetected boreholes (1.4.04.02.00)
Drilling activities (human intrusion) (1.4.04.00.00)
Geochemical interactions in geosphere (dissolution, precipitation, weathering) and effects on radionuclide transport (2.2.08.03.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Drilling fluid interacts with waste (1.4.04.01.01)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP.

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Drilling introduces surfactants (1.4.04.01.02)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP.

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Direct exposure to waste in mud pit (1.4.04.01.03)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP. However, it involves material brought to the surface and direct exposure of the drillers and is, therefore, excluded from the human-intrusion scenario.

Screening and Disposition: Excluded from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Flooding of drifts with drilling fluids (1.4.04.01.04)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP.

Screening and Disposition: Included in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Drilling fluid flow (1.4.04.01.05)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP.

Screening and Disposition: Included in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Drilling fluid loss (1.4.04.01.06)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP.

Screening and Disposition: Included in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Blowouts (1.4.04.01.07)

Relationship to Primary FEP: This FEP description addresses the potential flow through the borehole from a pressurized zone to a thief zone, rather than materials brought to the surface. This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP.

Screening and Disposition: Included in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Drilling-induced geochemical changes (1.4.04.01.08)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP

Screening and Disposition: Included in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Fluid injection-induced geochemical changes (1.4.04.01.09)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP.

Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Cuttings (1.4.04.01.10)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP. However, it involves material brought to the surface and direct exposure of the drillers and is, therefore, excluded from the human-intrusion scenario.
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Cavings (1.4.04.01.11)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP. However, it involves material brought to the surface and direct exposure of the drillers and is, therefore, excluded from the human-intrusion scenario.
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

<u>*Secondary FEP Name and Number:*</u> Spallings (1.4.04.01.12)

Relationship to Primary FEP: This is a possible effect of drilling activities and is, therefore, addressed in the Primary FEP. However, it involves material brought to the surface and direct exposure of the drillers and is, therefore, excluded from the human-intrusion scenario.
Screening and Disposition: *Excluded* from the TSPA–SR – By Regulation

6.2.22 Mining and Other Underground Activities (Human Intrusion) (1.4.05.00.00)

FEP Description: Mining and other underground human activities (e.g., tunneling, underground construction, quarrying) could disrupt the disposal system.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—By Regulation

Screening Argument: "Mining and other underground activities (human intrusion)" and the Secondary FEPs are *Excluded* from the TSPA–SR and the human-intrusion scenario based on regulation. All related Secondary FEPs are also *Excluded.* Consistent with regulatory specifications, the only mechanism of intrusion to be considered in the human-intrusion scenario is intersection [or penetration] of the repository by a single borehole (proposed rule 40 CFR 197: 64 FR 46976, §197.26 (a - f) and proposed rule 10 CFR 63: 64 FR 8640, §63.113(d)).

At proposed rule 10 CFR 63 (64 FR 8640, Section XI. Human Intrusion), the supplemental text provides a description of the NRC's considerations in the use of a stylized human-intrusion scenario. These considerations provide that:

> The Commission does not intend to speculate on the virtual infinity of human intrusion scenarios that could be contemplated, nor does it intend for this analysis to address the full range of possible intrusions that could occur.

This statement implies that the NRC is not primarily concerned with addressing the motivation or range of specific methodologies that might be involved in a human-intrusion scenario, but rather "intends that this analysis show that the repository exhibits some resilience to a breach of engineered and geologic barriers from events that are reasonably of concern." The Commission then proposes that the DOE use "current practices for resource exploration to establish properties for the intrusion scenario," and then specifies the type of intrusion to be considered at proposed rule 10 CFR §63.113(d) (64 FR 8640).

Regardless of the regulatory specification of a stylized human-intrusion scenario, mining for resources is unlikely at Yucca Mountain. Extensive review of the potential for occurrences of natural resources at Yucca Mountain has concluded that no currently economic resources occur at the site, nor are any likely to be found in the future (DOE 1998, Section 2.2.7.3).

TSPA Disposition: "Mining and other underground activities" and the Secondary FEPs are *Excluded* from the TSPA–SR and from the human-intrusion scenario as described in the Screening Argument.

Supplemental Discussion: Mining for resources contained within the repository (e.g., for the recovery of fissionable material or for materials used in the engineered barriers) would constitute deliberate intrusion (see Section 6.2.17 "Deliberate human intrusion" (1.4.02.01.00)) and is *Excluded* from the TSPA–SR based on regulatory specifications.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>*Directly Affected Subissues*</u>
TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

<u>*Integrated Subissues/Related Subissues*</u>
ENG2 Eng: Mechanical Disruption of Engineered Barriers: CLST2, CLST6

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Records and markers, repository (1.1.05.00.00)
Administrative control, repository site (1.1.10.00.00)

Social and institutional developments (1.4.08.00.00)
Urban and industrial land and water use (2.4.10.00.00)
Explosions and crashes (1.4.11.00.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Deliberate human intrusion (1.4.02.01.00)
Inadvertent human intrusion (1.4.02.02.00)
Drilling activities (human intrusion) (1.4.04.00.00)
Effects of drilling intrusion (1.4.04.01.00)
Altered soil or surface water chemistry (1.4.06.01.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Mine shaft intersects waste container (1.4.05.00.01)

Relationship to Primary FEP: This is a particular consequence of mining activities and is, therefore, addressed in this Primary FEP. It also deals with materials

brought to the surface, and is therefore, excluded from the TSPA–SR.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> A mine shaft creates a preferential path through the upper non-welded unit and a wetter zone develops (1.4.05.00.02)

Relationship to Primary FEP: This is a particular consequence of mining activities and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Intrusion (mining) (1.4.05.00.03)

Relationship to Primary FEP: This is a particular consequence of mining activities and is, therefore, addressed in this Primary FEP. The critical group is specified by YMP regulations, and specifically excludes the miners from consideration as suggested by the description.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Mines (1.4.05.00.04)

Relationship to Primary FEP: This is a particular consequence of mining activities and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Solution mining (1.4.05.00.05)

Relationship to Primary FEP: This is a particular type of mining activity and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Water from mining above the repository drains through the repository (1.4.05.00.06)

Relationship to Primary FEP: This is a particular consequence of mining activities and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Underground dwellings (1.4.05.00.07)

Relationship to Primary FEP: This is a particular type of underground construction threat would require tunneling and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Resource mining (1.4.05.00.08)

Relationship to Primary FEP: No description is provided in the source document. It is inferred that this is a particular type of underground activity and it is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Tunneling (1.4.05.00.09)

Relationship to Primary FEP: No description is provided in the source document. It is inferred that this is a particular type of underground activity and it is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Underground construction (1.4.05.00.10)

Relationship to Primary FEP: No description is provided in the source document. It is inferred that this is a particular type of underground activity and it is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Quarrying, near surface extraction (1.4.05.00.11)

Relationship to Primary FEP: No description is provided in the source document. It is inferred that this is a particular type of quarrying, and it is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Mining activities (1.4.05.00.12)

Relationship to Primary FEP: This is particular to sites in Switzerland, but pertains to mining. It is retained in the FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Potash mining (1.4.05.00.13)

Relationship to Primary FEP: This is a particular type of mining activity and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Other resources (1.4.05.00.14)

Relationship to Primary FEP: This is specific to WIPP. It is redundant with other Secondary FEPs and is retained in the FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Tunneling (1.4.05.00.15)

Relationship to Primary FEP: This is specific to WIPP. It is redundant with other Secondary FEPs and is retained in the FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Construction of underground facilities (1.4.05.00.16)

Relationship to Primary FEP: This is specific to WIPP. It is redundant with other Secondary FEPs and is retained in the FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Archaeological excavations (1.4.05.00.17)

Relationship to Primary FEP: This is specific to WIPP. It is redundant with other Secondary FEPs and is retained in the FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Deliberate mining intrusion (1.4.05.00.18)

Relationship to Primary FEP: This is specific to WIPP. It is redundant with other Secondary FEPs and is retained in the FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Heat storage in lakes or underground (1.4.05.00.19)

Relationship to Primary FEP: This is a particular type of underground construction that would require tunneling and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Changes in groundwater flow due to mining (1.4.05.00.20)

Relationship to Primary FEP: This is specific to WIPP. It is redundant with other Secondary FEPs and is retained in the FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Changes in geochemistry due to mining (1.4.05.00.21)

Relationship to Primary FEP: This is specific to WIPP. It is redundant with other Secondary FEPs and is retained in the FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

6.2.23 Explosions and Crashes (Human Activities) (1.4.11.00.00)

FEP Description: Explosions or crashes resulting from future human activities may affect the long-term performance of the repository. Explosions may result from nuclear war, underground nuclear testing or resource exploitation.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—By Regulation

Screening Argument: "Explosions and crashes (human activities)" and all Secondary FEPs are *Excluded* from the TSPA–SR and the human-intrusion scenario based on regulation.

Proposed rule 40 CFR §197.12 (64 FR 46976) defines human intrusion as "...breaching of any portion of the Yucca Mountain Disposal system by human activity." The Yucca Mountain disposal system is defined as "the combination of underground engineered and natural barriers at the Yucca Mountain site which prevents or substantially reduces releases from the disposed radioactive material." Consequently, any human activity or human-induced activity (including all external or intentional internal explosions) which has a significant negative impact on the barrier system is, by definition, human intrusion.

Proposed rule 40 CFR 197 (64 FR 46976, §197.26(a - f)) and proposed rule 10 CFR 63 (64 FR 8640, §63.113(d)) clearly stipulate that human intrusion shall be considered only through the specified stylized drilling scenario.

TSPA Disposition: "Explosions and crashes (human activity)" and all Secondary FEPs are *Excluded* from the TSPA–SR and the human-intrusion scenario as described under the Screening Argument.

Supplemental Discussion: None

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening

TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

Integrated Subissues/Related Subissues

ENG2 Eng: Mechanical Disruption of Engineered Barriers: CLST2, CLST6

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Records and markers, repository (1.1.05.00.00)
Administrative control, repository site (1.1.10.00.00)
Deliberate human intrusion (1.4.02.01.00)
Inadvertent human intrusion (1.4.02.02.00)
Drilling activities (human intrusion) (1.4.04.00.00)
Mining and other underground activities (1.4.05.00.00)
Social and institutional developments (1.4.08.00.00)
Urban and industrial land and water use (2.4.10.00.00)

Links to FEPs that examine similar consequences and effects:

Meteorite impacts (1.5.01.01.00)
Gas explosions (2.1.12.08.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Bomb blast (1.4.11.00.01)

Relationship to Primary FEP: This is a particular type of explosion and is, therefore, addressed in this Primary FEP.
Screening and Disposition: Excluded from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Collisions, explosions, and impacts (1.4.11.00.02)

Relationship to Primary FEP: These are particular types of explosion, and are, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Underground test of nuclear devices (1.4.11.00.03)

Relationship to Primary FEP: This is a particular type of explosion and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Explosions (1.4.11.00.04)

Relationship to Primary FEP: This is a generic mention of explosion due to sabotage and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Nuclear War (1.4.11.00.05)

Relationship to Primary FEP: This is a particular type of explosion and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Underground nuclear testing (1.4.11.00.06)

Relationship to Primary FEP: No description is provided in the source document. It is inferred that this is a particular type of explosion and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Explosions for resource recovery (1.4.11.00.07)

Relationship to Primary FEP: This is a particular type of explosion and potential consequences are listed and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

<u>*Secondary FEP Name and Number:*</u> Underground nuclear device testing (1.4.11.00.08)

Relationship to Primary FEP: This is a particular type of explosion and potential consequences are listed and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

Secondary FEP Name and Number: Changes in groundwater flow due to explosions (1.4.11.00.09)

Relationship to Primary FEP: This is a particular type of explosion and potential consequences are listed and is, therefore, addressed in this Primary FEP.
Screening and Disposition: *Excluded* from the TSPA–SR—By Regulation

6.2.24 Meteorite Impact (1.5.01.01.00)

FEP Description: Meteorite impact close to the repository site might disturb or remove rock so that radionuclide transport to the surface is accelerated. Possible effects include alteration of flow patterns (faults, fractures), changes in rock stress, cratering and exhumation of waste.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—Low probability (for direct exhumation, direct fracturing to repository horizon)

Excluded from the TSPA–SR—Low consequence to dose (for alteration of flow paths, fracturing of overlying geologic units, and for changes in rock stress)

Screening Argument: "Meteorite impact" and the Secondary FEPs are *Excluded* from the TSPA–SR based on low probability for exhumation, fracturing to repository depth, or fracturing through the Paintbrush non-welded tuff above the repository. It is *Excluded* based on low consequence to dose for increased infiltration in the UZ, resulting from the impact in the outcrop area adjacent to the waste emplacement area. Probability calculations and a discussion of meteorite impact probability and cratering data are provided in Attachment IIB, and are the basis for the following screening arguments.

It is assumed that the depth of the repository, a design parameter, can be used as part of the justification for exclusion of the FEP (Assumption 5.2 of this document, ANL-WIS-MD-000019), and that the repository will be constructed according to the design used as the basis for the screening (Assumption 5.3 of this document, ANL-WIS-MD-000019). Accordingly, the probability of the occurrence of meteorite cratering in the repository area has been calculated and is provided in Attachment IIB. The analysis is based on the maximum design- repository-footprint area and on a 250-m depth to the top of the repository (Assumption 5.5.6 of this document, ANL-WIS-MD-000019). The analyses are based on current data for meteorites and astroblemes, and cratering statistics, taken from peer reviewed literature, as described in Assumptions 5.5.1 through 5.5.9 of this document, ANL-WIS-MD-000019.

As calculated in Attachment IIB, the threat of direct exhumation is below the probability cutoff for events and processes to be considered. The crater diameter (80-m diameter) that corresponds to the 10^{-8} (or 1 E-08) annual recurrence frequency (see Assumption 5.7 of this document, ANL-WIS-MD-000019) is of insufficient size to exhume waste, produce a crater whose fractures reach the repository depth, or to fracture to a depth of more than about 60 m. Larger crater diameters occur less frequently and are therefore of lower probability and are, therefore, *Excluded* from the

TSPA–SR. Smaller crater diameters occur more frequently, but are of insufficient size to result in direct exhumation.

Fracturing of the geologic units above the repository is also of concern form the standpoint of altering flow paths. Increased fracturing could result in increased downward groundwater flux. The Paintbrush nonwelded tuff unit plays a significant role in slowing downward water movement to the repository horizon (DOE 1999, p. 3-46). With regards to fracturing from a meteorite impact extending to the top of or through the Paintbrush nonwelded tuff, however, the probability of a meteorite impact sufficient to cause such fractures above the waste emplacement area is also less than the probability threshold of 10^{-8} (or 1 E-08) annual recurrence frequency (Assumption 5.7 of this document, ANL-WIS-MD-000019). Smaller crater diameters occur more frequently, but are of insufficient size to result in fracturing to the top of or through the Paintbrush nonwelded tuff unit.

Impacts on infiltration from fracturing above the waste emplacement area, and shallower than the top of the Paintbrush nonwelded tuff unit were also considered. The threshold crater diameter size is approximately 80 m, based on a depth of 60 m to the top of the Paintbrush Unit, and a fracture depth - to - crater diameter ration of 0.76. The regulatory probability of $10^{-4}/10^{4}$ years (or 1 E-04/1 E04) (Assumption 5.7 of this document, ANL-WIS-MD-000019) is exceeded for craters of less than 80-m diameter, based on an assumed meteoroid entry velocity of 15 km/sec (Assumption 5.5.3). The 80-meter size is likely over-stated since the calculation in Attachment IIB is based on the most conservative of the analyses (i.e., assuming a fracture depth - to - crater diameter ration of 0.76). With less conservative, but still realistic assumptions, the crater diameter of interest could in fact be as low as 20 m (i.e., a 20-m diameter crater corresponds to the regulatory probability threshold of $10^{-4}/10^{4}$ years (or 1 E-04/1 E04) (Assumption 5.7 of this document, ANL-WIS-MD-000019)). Regardless, an 80-m diameter crater encompasses an area of approximately .005 km^2 compared to the maximum total repository surface area of 11.1 km^2, or approximately 0.04 percent of the land surface above the repository. The percentage of the land surface affected drops to less than .003 percent for the 20-m diameter crater. Consequently, if an impact were to occur, only a limited surface area would be involved, and the Paintbrush nonwelded tuff unit would remain unaffected by these size cratering events. This suggests that infiltration over the waste emplacement area as a whole (as opposed to the limited impact-affected area) would not be significanlty altered, and increased infiltration due to meteorite impact does not present a mechanism to significantly increase dose. Consequently, meteorite cratering affecting performance through increased infiltration or other meteorite-induced surficial effects is *Excluded* based on low consequence to dose.

For the Paintbrush unit outcrop area (as opposed to the waste emplacement area), a crater diameter of 80 m of larger occurs at a 10^{-8} (or 1 E-08) annual frequency, for meteorites with entry velocities equal to 15 km/sec. Fracturing through the thin outcrop of the Paintbrush unit along the western edge of the repository could occur if the depth of fracturing to crater diameter exceeds a ratio of 0.25. For entry velocities equal to 20 km/sec, crater diameters of 25 m or larger occur at a 10^{-8} (or 1 E-08) annual frequency or less, and for the Grieve's distribution corresponds to a diameter of about 2 m. Because of the outcrop's location along the westward edge of the repository block, the minimal land surface affected by the threshold crater diameters, and the low probability of crater diameters larger than the threshold diameter, additional fracturing in the outcrop area would not significantly alter the unsaturated zone flow conditions within the repository. Therefore, increased infiltration due to meteorite impact on the outcrop does not present a mechanism to significantly increase dose. Consequently, meteorite cratering affecting performance through increased infiltration or other meteorite-induced surficial effects is *Excluded* based on low consequence to dose

The effects of changes in rock stress are addressed in *Features, Events, and Processes: Disruptive Events*, ANL-WIS-MD-00005 (CRWMS M&O 2000f, Sections 6.2.19 and 6.2.20), and are *Excluded* based on low consequence to dose. Changes in fracture apertures related to stress changes have a minimal impact on the hydrologic properties of the host rock.

Since infiltration is not significantly affected and no fracturing occurs down to the repository depth, there is no mechanism for the impact to affect flux through the repository horizon, and the dose is, therefore, not significantly changed. This portion of the FEP is, therefore, *Excluded* from the TSPA–SR based on low consequence to dose.

TSPA Disposition: "Meteorite impact" and the Secondary FEPs are *Excluded* from the TSPA–SR as described under the Screening Argument

Supplemental Discussion: See Attachment IIB for additional discussions and calculation of meteorite impact probabilities.

Related PMRs, AMRs, and Calculations: *Features, Events, and Processes: Disruptive Events* ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
RDTME3: Underground Facility Design and Performance

<u>Integrated Subissues/Related Subissues</u>

ENG2 Eng: Mechanical Disruption of Engineered Barriers/ CLST2, CLST6
UZ1 Geo: Spatial and Temporal Distribution of Flow / USFIC3, USFIC4, SDS3

Related Primary FEPs:

<u>Links to FEPs that examine related, but distinct, consequences and effects</u>:

Climate change (global) (1.3.01.00.00)
Extraterrestrial events (1.5.01.02.00)

Links to FEPs that examine similar consequences and effects:

Explosions and crashes (1.4.11.00.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Meteorite impact (1.5.01.01.01)

Relationship to Primary FEP: Description lists possible mechanism by which an impact could affect repository performance. The mechanism are included in the Primary FEP description
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

Secondary FEP Name and Number: Meteorite (1.5.01.01.02)

Relationship to Primary FEP: The description is specific to sites in Europe and suggests low probability of impact.
Screening and Disposition: *Excluded* from the TSPA–SR—Low probability

Secondary FEP Name and Number: Meteorite Impact (1.5.01.01.03)

Relationship to Primary FEP: No description is provided, retained in FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—Low Probability

Secondary FEP Name and Number: Impact of a large meteorite (1.5.01.01.04)

Relationship to Primary FEP: Description pertains to derivation of probabilities for WIPP site.
Screening and Disposition: *Excluded* from the TSPA–SR—Low Probability

6.2.25 Extraterrestrial Events (1.5.01.02.00)

FEP Description: Extraterrestrial events (e.g., supernova, solar flare, gamma-ray burster, alien life forms) may affect long-term performance of the disposal system.

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

Screening Argument: "Extraterrestrial events" is *Excluded* from the TSPA–SR based on low consequence to dose. No scientific basis exists to quantify or bound either the effect or probability of extraterrestrial events. The effect of any such past events is reflected in the existing geologic properties (Assumption 5.1 of this document, ANL-WIS-MD-000019) and the processes being evaluated within the TSPA. The geologic setting has been based on the evaluation of data representing more than a 10,000,000-year period of effects.

Consequently, a future event would either result in a range of parameters within those already measured and addressed in site models, and hence is of low consequence to dose, or it would be an infrequent event (less than once in 100,000 years) and, therefore, be of low consequence to the expected annual dose once probabilistically-weighted.

TSPA Disposition: "Extraterrestrial events" is *Excluded* from the TSPA–SR as described under the Screening Argument.

Supplemental Discussion: See Screening Argument

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening

Integrated Subissues/Related Subissues

None

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Meteorite impact (1.5.01.01.00)

Links to FEPs that examine similar consequences and effects:

Changes in the earth's magnetic field (1.5.03.01.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Extraterrestrial Events (1.5.01.02.01)

Relationship to Primary FEP: No description is provided. The FEP is presumed to be the same as the Primary FEP
Screening and Disposition: Same as the Primary FEP

6.2.26 Changes in the Earth's Magnetic Field (1.5.03.01.00)

FEP Description: Changes in the earth's magnetic field could affect the long-term performance of the repository.

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

Screening Argument: "Changes in the earth's magnetic field" and all Secondary FEPs are *Excluded* from the TSPA–SR based on low consequence to dose.

The magnetic field is known to affect the coupling of the earth with the solar wind (e.g., solar flares affecting weather); however, the form of the coupling is unknown. Among the possible effects of changes in the earth's magnetic field, only climate change has a reasonable possibility of affecting the repository. However, no clear evidence exists that climate change is connected with magnetic reversals, and therefore no basis exists for evaluating the range of possible future effects. Furthermore, the effect of any such past events is reflected in the range in climatic properties determined from field studies and observations, and that is being evaluated within the TSPA. Changes in the earth's magnetic field are extremely common in geologic history. Consequently, any significant cumulative effects of the changes in the earth's magnetic field is presumed to be reflected in the existing data for the hydrogeologic system. Because the existing data set includes the range of effects, future changes would presumably be no greater than those already considered, and therefore they would be of low consequence to dose.

Future climate changes from all natural causes are *Included* in the TSPA–SR (see "Climate change" (1.3.01.00.00).

TSPA Disposition: "Changes in the earth's magnetic field" and the Secondary FEPs are *Excluded* from the TSPA–SR as described under the Screening Argument.

Supplemental Discussion: See Screening Argument

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening

<u>Integrated Subissues/Related Subissues</u>

None

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Climate change, global (1.3.01.00.00).
Extraterrestrial events (1.5.01.02.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

None

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Flipping of the earth's magnetic poles (1.5.03.01.01)

Relationship to Primary FEP: Description links reversal (flipping) to increased solar radiation.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

<u>*Secondary FEP Name and Number:*</u> Changes of the magnetic field (1.5.03.01.02)

Relationship to Primary FEP: Description indicates that changes would have minimal impact on repository performance, retained in FEPs list for completeness.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

<u>*Secondary FEP Name and Number:*</u> Magnetic pole reversal (1.5.03.01.03)

Relationship to Primary FEP: Description links reversal of poles to climate change.
Screening and Disposition: *Excluded* from the TSPA–SR—Low consequence to dose

6.2.27 Earth Tides (1.5.03.02.00)

FEP Description: Small changes of the gravitational field due to celestial movements (sun and moon) cause earth tides and may, in turn, cause pressure variations in the groundwater flow systems.

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

Screening Argument: "Earth tides" is *Excluded* from the TSPA–SR based on low consequence to dose.

Earth tides are an on-going phenomenon and are reflected as rhythmic, measurable pressure increases and decreases. Consequently, any significant cumulative effects of earth tides can be assumed to be reflected in the existing data for the hydrogeologic system (Assumption 5.1 of this document, ANL-WIS-MD-000019). Earth tides are of such a small magnitude that any effect on the flow system, other than their measurement, is of low consequence to dose since the fluctuations are accounted for within the water level data used as the basis for the TSPA.

TSPA Disposition: "Earth tides" is *Excluded* from the TSPA–SR as described under the Screening Argument

Supplemental Discussion: See Screening Argument

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening

Integrated Subissues/Related Subissues

UZ2 Geo: Flow Paths in the UZ / USFIC4
SZ1 Geo: Flow Paths in the SZ / USFIC 4, USFIC5
SZ2 Geo: Radionuclide Transport in the SZ / USFIC6

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

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 FEPs that examine similar consequences and effects:

None

Treatment of Secondary FEPs: No Secondary FEPs

6.2.28 Salt Creep (2.2.06.05.00)

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.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—By Regulation

Screening Argument: "Salt creep" is *Excluded* from the TSPA–SR based on proposed regulatory requirements (64 FR 8640, §63.114(a) and §63.115(a)(4)). The guidance specifies that the TSPA evaluate only the relevant site features, events, and processes. There are no rocks in the repository that are sufficiently plastic to creep in a manner similar to salt, and no large volume of evaporite deposits is known in the vicinity of Yucca Mountain. Salt Creep is, therefore, *Excluded* (see Assumption 5.1 of this document, ANL-WIS-MD-000019).

TSPA Disposition: "Salt creep" is *Excluded* from the TSPA–SR as described under the Screening Argument

Supplemental Discussion: Inclusion of this FEP would be inconsistent with the guidance at proposed rule 10 CFR 63 (64 FR 8640). The proposed rule specifies at §63.114(a) (64 FR 8640) that the performance assessment " (a) Include data related to the geology, hydrology, and geochemistry (including disruptive processes and events) of the Yucca Mountain site, and the surrounding region to the extent necessary . . .," and §63.115(a)(4) (64 FR 8640) directs a presumption of "evolution of the geologic setting consistent with present knowledge of natural processes." It would also be contrary to the scope and intent at proposed rule 10 CFR §63.21(c)(1)) (64 FR 8640), which specifies consideration and description of " . . features, events, and processes outside of the site to the extent the information is relevant and material to safety or performance of the geologic repository." Since no salt formations are present, "Salt creep" is not relevant.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>*Directly Affected Subissues*</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening

<u>*Integrated Subissues/Related Subissues*</u>

None

Related Primary FEPs:

Links to FEPs that examine related, but distinct, consequences and effects:

Metamorphism (1.2.05.00.00)
Diapirism (1.2.09.01.00)
Effects of subsidence (2.2.06.04.00)

Links to FEPs that examine similar consequences and effects:

Salt diapirism and dissolution (1.2.09.00.00)
Large scale dissolution (1.2.09.02.00)

Treatment of Secondary FEPs: No Secondary FEP

6.2.29 Effects of Repository Heat on the Biosphere (2.3.13.03.00)

FEP Description: The heat released from radioactive decay of the waste will increase the temperatures at the surface above the repository. This could result in local or extensive changes in the ecological characteristics.

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

Screening Argument: "Effect of repository heat on the biosphere" is *Excluded* from the TSPA–SR based on low consequence to dose.

The effects of repository heat on the biosphere are summarized by DOE (1999, Section 5.9) based on work by CRWMS M&O (1999d, p. 46) and are chiefly related to concerns with transition from perennial to annual plant species. Evaluation of effects on flora and fauna are not within the scope of the TSPA.

A potential effect of the shift in species is a change in water infiltration, with increases in infiltration being of greater concern. The average infiltration is estimated to be between 4.5 and 6.5 mm/yr (DOE 1999, p.3-44). Infiltration rates are addressed in the Unsaturated Zone flow-and-transport model (CRWMS M&O 2000c, Section 3.2.2). The simulated average net infiltration ranges is based on present conditions and on analogs for future climate conditions. The TSPA model includes the evaluation of infiltration related to three climatic stages, including related vegetative changes, and the resulting consequence to dose (CRWMS M&O 2000c, Section 3.2.1). Consequently, any changes in infiltration (and related consequence to dose) due to vegetative changes caused strictly by the effects of repository heat on the biosphere are of low consequence to dose because they are bounded by the vegetative changes modeled in association with the climate fluctuations.

TSPA Disposition: "Effect of repository heat on the biosphere" is *Excluded* from the TSPA–SR as described under the Screening Argument. The increases in net infiltration are reflected in the output of the UZ flow model.

Supplemental Discussion: In the draft EIS (DOE 1999, Section 5.9), it states that "predicted increases in surface soil temperatures range to 6°C (10.8°F) for dry soil at a depth of 2 meters (6.6 feet)." As stated in the draft EIS, a temperature increase of 3°C (5.4°F) could affect root growth and other soil parameters such as the growth of microbes or nutrient availability. In general, areas affected by repository heating could experience a loss of shrub species and an increase in annual species. It is expected that a shift in plant composition, if any, would be limited to the area within 500 meters of the repository footprint. Changes in the plant community could lead to an increase in the amount of rainfall runoff and, therefore, an increase in the erosion of surface soil. Change in water infiltration is potentially affected by a number of factors such as, increases and decreases in vegetation and vegetation type, climate changes, total precipitation, air temperature, runoff, solar heating, and characteristics of the soil matrix.

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>Directly Affected Subissues</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
RDTME3 Underground Facility Design and Performance
ENFE1 Flow and Seepage
ENFE2 Waste Package Environment
TEF3 Effects on Flow

<u>Integrated Subissues/Related Subissues</u>

ENG1 Eng: Degradation of Engineered Barriers / CLST1, CLST2, CLST6

Related Primary FEPs:

<u>Links to FEPs that examine related, but distinct, consequences and effects</u>:

Nonuniform heat distribution / edge effects in repository (2.1.11.02.00)
Thermally-induced stress changes in waste and EBS (2.1.11.07.00)

<u>Links to FEPs that examine similar consequences and effects</u>:

Heat output / temperature in waste and EBS (2.1.11.01.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.2.30 Atmospheric Transport of Contaminants (3.2.10.00.00)

FEP Description: This category contains FEPs related to transport of contaminants in the atmosphere. Atmospheric transport includes radiotoxic and chemotoxic species in the air as gas, vapor, particulates or aerosol. Transport processes include wind, plowing and irrigation, degassing, saltation, and precipitation.

Screening Decision and Regulatory Basis: *Included* in the TSPA–SR—Does not satisfy a screening criterion (for transport mechanisms and species (via ashfall))

Excluded from the TSPA–SR—Low consequence to dose (for volatile radionuclides as a gaseous release through the host rock)

Screening Argument: "Atmospheric transport of contaminants" of volatile radionuclides is *Excluded* from the TSPA–SR based on low consequence to dose.

The most current repository design (CRWMS M&O 2000a and 2000b) indicates disposal of between 11,000 and 15,000 total waste packages. If each waste package contains 0.234 to 0.673 Ci of gaseous C-14 per package (Assumption 5.6 of this document, ANL-WIS-MD-000019), the total available gaseous source term is between 3000 and 11,000 Ci.

The potential for gaseous release during the postclosure performance is discussed in Section 5.5 of the draft EIS (DOE 1999). The referenced discussion is based on a gas-phase inventory of 0.234 curie of Carbon-14 per waste package of commercial spent nuclear fuel. The release rate is based on the estimated timeline of container failures for a high thermal load scenario, using average values for the random parameters used for the analysis. Restriction of the release rate due to the presence of the fuel-rod cladding was assumed. The estimated maximum release rate is 9.8×10^{-8} (or 9.8 E-08) curies per year. The analysis estimated human health impacts for population within an 84-kilometer radius of the repository. The GENII code was used to model the atmospheric transport and human uptake of the released Carbon 14. The model suggested a 7.8×10^{-15} (or 7.8 E -15) rem/yr average dose (7.8×10^{-12} (or 7.8 E-12) mrem/yr) to individuals in the population.

In the Background Information Document for proposed rule 40 CFR 197, (EPA 1999, Section 9.2), the EPA addresses the issue of gaseous releases as a secondary pathway for human exposure and assesses bounding values for human doses. The EPA states that the radionuclide with the highest potential for gaseous release and human exposure is carbon-14. The EPA estimates that a global dose involving the release of the entire repository of 91,000 curies (both solid and gas) of C-14 through time would result in an average individual dose of only 0.0003 mrem/yr (3×10^{-4} mrem/yr).

The EPA also calculated local dose estimates for a single waste package. It was assumed that 0.673 curies/waste package could be involved in a quick release. Release from a single package gives a dose on the order of 0.00013 mrem/yr (or about 1.3 x 10^{-4} mrem/yr). The EPA also states that the estimated value is a conservative upper bound estimate due to dissolution in pore waters and partitioning between fractures and the matrix porosity voids. The EPA also states that gaseous carbon-14 releases after initial breaching are likely to be less than the instantaneous release fraction.

The conditional calculated doses (i.e., conditional on time-distributed failure or on single package failure) are substantially below the expected annual dose calculated for overall repository performance at all times during the 10,000-year regulatory period. As shown in the TSPA–SR documentation (CRWMS M&O 2000c, Figures 4.2.1 and 4.3.3), the expected annual dose, which is dominated by the igneous disruption scenario throughout the regulatory period, exceeds 0.003 mrem/year (3 x 10^{-3} mrem/year) at all times during the first 10,000 years. Thus, atmospheric releases from time-distributed failure or the failure of a single package will not have a significant effect on the expected annual dose, regardless of the probability of such a failure occurring.

Atmospheric releases from the simultaneous failure of multiple packages could potentially result in a significant effect on the expected annual dose, but the conditional dose associated with the simultaneous failure of multiple packages should be weighted by the probability of such an event occurring. The only event identified for the TSPA–SR that results in simultaneous failure of multiple packages is igneous disruption, with a mean annual probability of 1.6 x 10^{-8} (or 1.6 E-08; CRWMS M&O 2000j, Table 13). Atmospheric releases of radioactive volatiles resulting from igneous disruption can be considered through a bounding analysis.

Using the EPA approach described above, and assuming a linear relationship between source term and dose, the simultaneous failure of 11,000 packages (somewhat more than the total proposed for the repository) would result in an atmospheric dose from radioactive volatiles of 1.43 mrem/yr (calculated as 0.00013 mrem/yr per package times 11,000 packages). Comparison of this conditional dose (i.e., the dose is conditional on the simultaneous failure of 11,000 waste packages) to the expected annual dose requires weighting the dose by the probability of its occurrence. The probability of a simultaneous failure of all packages is uncertain, but is adequately bounded for the purposes of this analysis by the probability of igneous disruption, given that igneous disruption is the only event identified that damages multiple packages and given that the possible damage from an igneous event is bounded by the full inventory of the repository. Thus, the estimate of 1.43 mrem/yr for atmospheric releases of radioactive volatiles from 11,000 packages should be multiplied by the annual probability of 1.6 x 10^{-8} (or 1.6 E-08) to yield a maximum probability-weighted dose from atmospheric releases of 2.3 x 10^{-8} (or 2.3 E-08) mrem/yr. This number is far below the calculated expected annual dose throughout the regulatory period, which is dominated by other pathways associated with igneous disruption and is calculated in the TSPA–SR to exceed 0.003 mrem/yr at all times during the first 10,000 years, as discussed above.

In summary, release of radioactive volatiles is *Excluded* based on low consequence to dose because calculated doses from the time-distributed failure of multiple packages or failure of a single package do not have a significant effect on the expected annual dose, regardless of the probability of such a failure during the regulatory period. Doses could be higher from the simultaneous failure of multiple packages, but such doses should be weighted by the probability of simultaneous failures. A bounding consideration of the failure of all packages in the repository during igneous disruption, which is the only event identified in the TSPA–SR that leads to simultaneous failure of multiple packages, indicates that the probability-weighted dose from release of radioactive volatiles associated with such an event is roughly five orders of magnitude below the expected annual dose.

Consequently, release of volatiles is *Excluded* based on low consequence to dose because an insufficient source term exists to result in exceeding the recommended dose limit.

TSPA Disposition: "Atmospheric transport of contaminants" is *Excluded* from the TSPA–SR for volatile radionuclides as a gaseous release through the host rock, as described under the Screening Argument.

Atmospheric transport due to volcanic ashfall is *Included* in the TSPA–SR within the disruptive scenario and is summarized in "Ashfall" (1.2.04.07.00) (CRWMS M&O 2000d, Appendix D and CRWMW M&O 2000f, Section 6.2.14). The direct deposition of ashfall in the reference biosphere (see Section 4.2.2.3) in the vicinity of the critical group (see Section 4.2.2.4) represents an upper bound on the source term for atmospheric transport mechanisms leading to the exposure of the critical group (see Section 4.2.2.4). Transport mechanisms within the reference biosphere described for the Secondary FEPs (see Table 4 in Section 7) have also been considered and are *Included* in the TSPA–SR for biosphere considerations under "Inhalation" (3.3.04.02.00) and "Agricultural land use and irrigation" (2.4.09.01.00) (CRWMS M&O 2000d, Appendix D).

Supplemental Discussion: See *Screening Argument*

Related PMRs, AMRs, and Calculations: *Features, Events, and Processes: Disruptive Events* ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

IRSR Issues:

Directly Affected Subissues

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity
IA2: Igneous Activity Consequence
RDTME3: Underground Facility Design and Performance

Integrated Subissues/Related Subissues

Direct1 Geo: Volcanic Disruption of Waste Packages / IA1, IA2
ENG2 Eng: Mechanical Disruption of Waste Packages / CLST2, CLST5, IA2, RDTME3

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Basaltic cinder cone erupts through the repository (1.2.04.03.00)
Radionuclide accumulation in soil (2.3.02.02.00)
Soil and sediment transport (2.3.02.03.00)
Agricultural land use and irrigation (2.4.09.01.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Ashfall (1.2.04.07.00)
Precipitation (2.3.11.01.00)
Biosphere transport (2.3.13.02.00)
Ingestion (3.3.04.01.00)
Inhalation (3.3.04.02.00)
Radiological toxicity / effects (3.3.06.00.00)
Non-radiological toxicity / effects (3.3.07.00.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Suspension in air (3.2.10.00.01)

Relationship to Primary FEP: This addresses both the form and medium of radionuclides and the mechanisms for atmospheric transport and is, therefore, addressed in the Primary FEP.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Wind (3.2.10.00.02)

Relationship to Primary FEP: This addresses a particular transport mechanism for radionuclides in the atmosphere and is, therefore, addressed in the Primary FEP.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

<u>*Secondary FEP Name and Number:*</u> Radionuclide volatilization / aerosol/ dust production (3.2.10.00.03)

Relationship to Primary FEP: This addresses the form and medium of radionuclides for atmospheric transport and is, therefore, addressed in the Primary FEP.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Convection, turbulence, and diffusion (atmospheric) (3.2.10.00.04)

Relationship to Primary FEP: This addresses a particular transport mechanism for radionuclides in the atmosphere and is, therefore, addressed in the Primary FEP.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Deposition (atmospheric) (3.2.10.00.05)

Relationship to Primary FEP: This addresses a particular transport mechanism for radionuclides in the atmosphere and is, therefore, addressed in the Primary FEP.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Saltation (3.2.10.00.06)

Relationship to Primary FEP: This addresses a particular transport mechanism for radionuclides in the atmosphere and is, therefore, addressed in the Primary FEP.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Atmosphere (3.2.10.00.07)

Relationship to Primary FEP: This addresses the form and medium of radionuclides for atmospheric transport and is, therefore, addressed in the Primary FEP.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

Secondary FEP Name and Number: Precipitation (meteoric) (3.2.10.00.08)

Relationship to Primary FEP: This addresses a particular transport mechanism for radionuclides in the atmosphere and is, therefore, addressed in the Primary FEP.
Screening and Disposition: *Included* in the TSPA–SR, as described in the TSPA Disposition

6.2.31 Toxicity of Mined Rock (3.3.06.01.00)

FEP Description: Excavation of the repository and/or its contents may result in the production of tailings, which may subsequently release toxic contaminants.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—By Regulation

Screening Argument: The handling of excavation spoils during construction is an operational concern. "Toxicity of mined rock" is, therefore, *Excluded* from the TSPA, which is focused on postclosure assessment.

Excavation or mining of the repository after closure is considered as deliberate human intrusion and is *Excluded* from the TSPA–SR and the human-intrusion scenario based on regulation. Proposed rule 40 CFR 197 (64 FR 46976, Section III.E. What is the Standard for Human Intrusion?) is explicit with regard to excluding a specific deliberate intrusion.

Furthermore, at proposed rule 10 CFR 63 (64 FR 8640, Section XI. Human Intrusion), the supplemental text provides description of the NRC's considerations in the use of a stylized human-intrusion scenario. These considerations include the statement, "Hazards to the intruders themselves (drillers, miners, etc.) or to the public from material brought to the surface by the assumed intrusion should not be included in this analysis, according to NAS."

TSPA Disposition: "Toxicity of mined rock" is *Excluded* from the TSPA–SR as described under the Screening Argument.

Supplemental Discussion: See Screening Argument

Related PMRs, AMRs, and Calculations: None

IRSR Issues:

<u>*Directly Affected Subissues*</u>

TSPAI 1: Features, Events, and Processes Identification and Screening
TSPAI 2: FEPs Identification, Classification, and Screening
TSPAI 3: Model Abstraction / Data Use and Validity

<u>*Integrated Subissues/Related Subissues*</u>

ENG2 Eng: Mechanical Disruption of Engineered Barriers: CLST2, CLST6

Related Primary FEPs:

<u>*Links to FEPs that examine related, but distinct, consequences and effects*</u>:

Geochemical interactions in geosphere (dissolution, precipitation, weathering) and effects on radionuclide transport (2.2.08.03.00)
Urban and industrial land and water use (2.4.10.00.00)

<u>*Links to FEPs that examine similar consequences and effects*</u>:

Mining and other underground activities (1.4.05.00.00)
Altered soil or surface water chemistry (1.4.06.01.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.3 CRITICALITY FEPs SCREENING AND ANALYSES

This section of the AMR addresses the 22 Primary FEPs that have been identified as Criticality Primary FEPs. These FEPs address conditions that have the potential to lead to criticality. Two conditions have been examined only on a preliminary basis: criticality of Department of Energy Spent Nuclear Fuel (DSNF) following igneous disruption, and near-field and far-field criticality of all waste types following an igneous intrusion. The only attachment specific to the Critiality FEPs is Attachment III, which provides descriptions for the Primary and Secondary FEPs.

Calculations are incomplete for criticality of DSNF following igneous disruption. Also evaluations of for near-field and far-field criticality following igneous disruption for all waste forms are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach. However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration-criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

6.3.1 Criticality in waste and EBS (2.1.14.01.00)

FEP Description: Nuclear criticality refers to a self-sustaining fission chain reaction that requires a sufficient concentration and localized (critical) mass of fissionable isotopes (e.g., U-235, Pu-239). Thermal criticality requires the additional presence of neutron moderating materials (e.g., water) in a suitable geometry. Fast criticality can occur without moderator, but generally requires a much larger critical mass than thermal criticality. Criticality can be prevented by the presence of neutron absorbing elements (e.g., boron, gadolinium). Within the waste and EBS, a critical mass may occur within the waste package (in-situ) or out of the waste package and in the drift (near-field). This FEP aggregates all mechanisms for in-situ and near-field criticality into a single category. Specific processes that could produce criticality are discussed in FEPs (2.1.14.03.00) through (2.1.14.08.00) (for in-situ) and in FEPs (2.1.14.09.00) through (2.1.14.14.00) (for out-of-container).

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low Probability (Preliminary for DOE spent nuclear fuel (DSNF) within the waste package following igneous intrusion, Preliminary for DSNF of combined fissile material for several DSNF waste packages in magma following igneous disruption, Preliminary for criticality of all waste types outside the waste package following igneous disruption).

Screening Argument: Criticality in the waste and the engineered barrier system (EBS) has been excluded from the TSPA–SR based on low probability of occurrence during the first 10,000 years of performance. Insofar, as this FEP aggregates all mechanisms for in-situ and near-field criticality into a single category, the screening decision should be considered preliminary for DSNF criticality within the waste package and for the possibility of combined fissile material from several DOE SNF waste packages in magma following igneous disruption. It is also preliminary for criticality of all waste types outside the waste package following igneous disruption.

As described in *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g), the probability of a nuclear criticality event within the waste and EBS at Yucca Mountain has been examined under conditions of nominal performance, potential damage due to seismicity, and igneous disruption. The probability of criticality in the waste and the EBS was shown to be less than one chance in 10,000 in the first 10,000 years following repository closure for nominal performance for all waste types. This conclusion included consideration of potential seismic effects. For the igneous disruption scenario, the probability of criticality in commercial spent nuclear fuel (CSNF), both within partially damaged packages and in fuel/magma mixtures that might occur following complete damage of packages, is also shown to be less than one chance in 10,000 in 10,000 years. The *Exclude* screening decision is preliminary because calculations are incomplete for criticality of defense spent nuclear fuel (DSNF) within the waste package or in magma following igneous disruption, and for criticality events of all waste types outside the package following igneous disruption, in both the near-field and far-field.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027 x 10^{-4}, 0:0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report* YMP-TR-004Q REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which was shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation*. ANL-EBS-PA-000002 (CRWMS M&O 2000h, Section 6.2.12: see the FEP, "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are excluded from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4), and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events, and Processes: Disruptive Events* ANL-WIS-MD-000005 REV 00 ICN 1: CRWMS M&O 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose.* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, excluded from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

Criticality following igneous disruption is examined in CRWMS M&O 2000g (Section 6.2) for both water-moderated configurations in partially damaged packages and silica-moderated configurations resulting from combinations of extensively damaged packages. For water-moderated CSNF criticality in partially damaged packages, the joint probability of igneous disruption and in-package criticality is calculated to be 1.8×10^{-7} (1.8 E-07) in 10,000 years (CRWMS M&O 2000g, Section 6.2.1).

The worst case of silica-moderated criticality following igneous intrusion involves the collection of the fissile material from several waste packages. This configuration is specifically addressed in FEP "Out-of-package criticality, fuel/magma mixture" (2.1.14.14.00). However, it is also a subset of this more general FEP, so the following screening explanation is given here. CSNF criticality in a spent-fuel/magma mixture was shown to be physically impossible (maximum $k_{eff} = 0.77$) even for the extraordinarily conservative assumption that the complete contents of seven waste packages could be arranged in an optimally-spaced cubic lattice (CRWMS M&O 2000g Section 6.2.2). Criticality in the waste package and EBS following igneous disruption is, therefore, excluded from the TSPA–SR based on low probability. The *Excluded* screening decision is preliminary because calculations are incomplete for criticality of DSNF following igneous disruption, and for criticality events of all waste types outside the package, in the EBS and far-field, following igneous disruption.

TSPA Disposition: Criticality in the waste and EBS has been excluded from the TSPA–SR based on low probability of occurrence.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs and Calculations:

Probability of Criticality Before 10,000 years CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: CLST 5, ENFE 5

Related Primary FEPs:

Critical Assembly Forms Away From Repository (2.2.14.01.00)

Criticality In-Situ, Nominal Configuration, Top Breach (2.1.14.02.00)

Criticality in-situ, waste package internal structures degrade faster than waste form, top breach (2.1.14.03.00)

Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach (2.1.14.04.00)

Criticality in-situ, waste package internal structures degrade slower than waste form, top breach (2.1.14.05.00)

Criticality in-situ, waste form degrades in place and swells, top breach (2.1.14.06.00)

Criticality in-situ, bottom breach allows flow through waste package, fissile material collects at bottom of waste package (2.1.14.07.00)

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place (2.1.14.08.00)

Near-field criticality, fissile material deposited in near field pond (2.1.14.09.00)

Near-field criticality, fissile solution flows into drift low point (2.1.14.10.00)

Near-field criticality, fissile solution is adsorbed or reduced in invert (2.1.14.11.00)

Near-field criticality, filtered slurry or colloidal stream collects on invert surface (2.1.14.12.00)

Near-field criticality associated with colloidal deposits (2.1.14.13.00)

Out-of-package criticality, fuel/magma mixture (2.1.14.14.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number*</u>: Criticality (in waste and EBS) (2.1.14.01.01)

Relationship to Primary FEP: Redundant, retained in FEP list for completeness.
Screening and Disposition: Same as the Primary FEP

<u>*Secondary FEP Name and Number*</u>: Criticality (in waste and EBS) (2.1.14.01.02)

Relationship to Primary FEP: Redundant, retained in FEP list for completeness.
Screening and Disposition: Same as the Primary FEP

<u>*Secondary FEP Name and Number*</u>: Nuclear criticality (in waste and EBS) (2.1.14.01.03)

Relationship to Primary FEP: Redundant, retained in FEP list for completeness.
Screening and Disposition: Same as the Primary FEP

<u>*Secondary FEP Name and Number*</u>: Nuclear criticality (in waste and EBS) (2.1.14.01.04)

Relationship to Primary FEP: Redundant, retained in FEP list for completeness.
Screening and Disposition: Same as the Primary FEP

<u>*Secondary FEP Name and Number*</u>: Nuclear criticality (in waste and EBS (2.1.14.01.05)

Relationship to Primary FEP: Redundant, retained in FEP list for completeness.
Screening and Disposition: Same as the Primary FEP

<u>*Secondary FEP Name and Number*</u>: Nuclear criticality: heat (in waste and EBS) (2.1.14.01.06)

Relationship to Primary FEP: Heat generation is one of the potential effects of criticality, and would be addressed in consequence analysis of criticality, if necessary.
Screening and Disposition: Same as the Primary FEP. Because criticality is screened out based on low probability, consequences of heat generation are not addressed specifically in the screening argument.

Secondary FEP Name and Number: Nuclear explosions (in waste and EBS) (2.1.14.01.07)

Relationship to Primary FEP: Nuclear explosions are a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the waste and EBS.

Screening and Disposition: Same as the Primary FEP. Because criticality is a necessary (but not sufficient) condition for a nuclear explosion, and because criticality is screened out based on low probability, the specific probability of nuclear explosions is not addressed explicitly in the screening argument.

Secondary FEP Name and Number: DOE SNF criticality in-situ (2.1.14.01.08)

Relationship to Primary FEP: Criticality in DOE SNF is a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the waste and EBS.

Screening and Disposition: Same as the Primary FEP. The screening argument for nominal performance for the Primary FEP is based on analyses of waste package performance that are valid for all waste forms. As noted in the screening argument for the primary FEP, the screening decision is preliminary for in-situ criticality in DOE SNF following igneous disruption.

Secondary FEP Name and Number: DOE SNF criticality in-situ (radionuclide inventory impact) (2.1.14.01.09)

Relationship to Primary FEP: Changes in radionuclide inventory are a possible effect of criticality, and would be addressed in consequence analysis of criticality, if necessary. Criticality in DOE SNF is a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the waste and EBS.

Screening and Disposition: Same as the Primary FEP. The screening argument for nominal performance for the Primary FEP is based on analyses of waste package performance that are valid for all waste forms. As noted in the screening argument for the primary FEP, the screening decision is preliminary for in-situ criticality in DOE SNF following igneous disruption.

Secondary FEP Name and Number: DOE SNF criticality near field (radionuclide inventory impact) (2.1.14.01.10)

Relationship to Primary FEP: Changes in radionuclide inventory are a possible effect of criticality, and would be addressed in consequence analysis of criticality, if necessary. Criticality in DOE SNF is a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the waste and EBS.

Screening and Disposition: Same as the Primary FEP. The screening argument for nominal performance for the Primary FEP is based on analyses of waste package performance that are valid for all waste forms. As noted in the screening argument for the primary FEP, the screening decision is preliminary for criticality in the EBS for all waste forms following igneous disruption.

Secondary FEP Name and Number: DOE SNF criticality in-situ (waste heat impact) (2.1.14.01.11)

Relationship to Primary FEP: Heat generation is one of the potential effects of criticality, and would be addressed in consequence analysis of criticality, if necessary. Criticality in DOE SNF is a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the waste and EBS.

Screening and Disposition: Same as the Primary FEP. The screening argument for nominal performance for the Primary FEP is based on analyses of waste package performance that are valid for all waste forms. As noted in the screening argument for the primary FEP, the screening decision is preliminary for in-situ criticality in DOE SNF following igneous disruption.

Secondary FEP Name and Number: DOE SNF criticality in-situ (waste package degradation impact) (2.1.14.01.12)

Relationship to Primary FEP: Degradation of the waste package is one of the potential effects of criticality, and would be addressed in consequence analysis of criticality, if necessary. Criticality in DOE SNF is a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the waste and EBS.

Screening and Disposition: Same as the Primary FEP. The screening argument for nominal performance for the Primary FEP is based on analyses of waste package performance that are valid for all waste forms. As noted in the screening argument for the primary FEP, the screening decision is preliminary for in-situ criticality in DOE SNF following igneous disruption.

Secondary FEP Name and Number: DOE SNF criticality in-situ (waste form degradation impact) (2.1.14.01.13)

Relationship to Primary FEP: Degradation of the waste form is one of the potential effects of criticality, and would be addressed in consequence analysis of criticality, if necessary. Criticality in DOE SNF is a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the waste and EBS.

Screening and Disposition: Same as the Primary FEP. The screening argument for nominal performance for the Primary FEP is based on analyses of waste package performance that are valid for all waste forms. As noted in the screening argument for the primary FEP, the screening decision is preliminary for in-situ criticality in DOE SNF following igneous disruption.

<u>*Secondary FEP Name and Number*</u>*:* DOE SNF criticality in-situ (cladding degradation impact) (2.1.14.01.14)

Relationship to Primary FEP: Degradation of the cladding is one of the potential effects of criticality, and would be addressed in consequence analysis of criticality, if necessary. Criticality in DOE SNF is a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the waste and EBS.

Screening and Disposition: Same as the Primary FEP. The screening argument for nominal performance for the Primary FEP is based on analyses of waste package performance that are valid for all waste forms. As noted in the screening argument for the primary FEP, the screening decision is preliminary for in-situ criticality in DOE SNF following igneous disruption.

<u>*Secondary FEP Name and Number*</u>*:* Differential solubility of neutron poisons (2.1.14.01.15)

Relationship to Primary FEP: This is a general process that is potentially relevant to all criticality FEPs. The secondary FEP is appropriately mapped to the Primary FEP addressing general in-situ criticality, but also could have been mapped to all other Primary criticality FEPs. Differential solubility of neutron poisons is considered in the evaluation of all criticality FEPs as appropriate, and screening decisions are unaffected by the mapping decision. *(Note: This FEP was initially identified as (2.1.14.10.02) in Rev. 00 of the YMP FEPs Database (CRWMS M&O 2000d, Appendix D). The numbering used here (2.1.14.01.15) reflects the current and more appropriate mapping to the in-situ criticality FEPs where the process is potentially of the greatest significance.)*

Screening and Disposition: Same as the Primary FEP

<u>*Secondary FEP Name and Number*</u>*:* Selective leaching of fissile materials (2.1.14.01.16)

Relationship to Primary FEP: This is a general process that is potentially relevant to all criticality FEPs. The secondary FEP is appropriately mapped to the Primary FEP addressing general in-situ criticality, but also could have been mapped to all other Primary criticality FEPs. Selective leaching of fissile materials is considered in the evaluation of all criticality FEPs as appropriate, and screening decisions are unaffected by the mapping decision (*Note: This FEP was initially identified as (2.1.14.10.03) in Rev. 00 of the YMP FEPs Database (CRWMS M&O 2000d, Appendix D). The numbering used here (2.1.14.01.16) reflects the current and more appropriate mapping to the in-situ criticality FEPs where the process is potentially of the greatest significance.)*

Screening and Disposition: Same as the Primary FEP

<u>*Secondary FEP Name and Number*</u>*:* Differential solubility of fissile isotopes (2.1.14.01.17)

Relationship to Primary FEP: This is a general process that is potentially relevant to all criticality FEPs. The secondary FEP is appropriately mapped to the Primary

FEP addressing general in-situ criticality, but also could have been mapped to all other Primary criticality FEPs. Differential solubilities of fissile isotopes considered in the evaluation of all criticality FEPs as appropriate, and screening decisions are unaffected by the mapping decision. *(Note: This FEP was initially identified as (2.1.14.11.01) in Rev. 00 of the YMP FEPs Database [CRWMS M&O 2000d, Appendix D]. The numbering used here (2.1.14.01.17) reflects the current and more appropriate mapping to the in-situ criticality FEPs where the process is potentially of the greatest significance.)*
Screening and Disposition: Same as the Primary FEP

6.3.2 Criticality In-Situ, Nominal Configuration, Top Breach (2.1.14.02.00)

FEP Description: The waste package internal structures and the waste form remain intact (nominal configuration). There is a breach near the top of the waste package, which allows water to collect in the waste package. Criticality then occurs in-situ.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—Low Probability

Screening Argument: In-situ criticality in the nominal configuration following a breach in the top of the waste package has been excluded from the TSPA-SR based on low probability of occurrence during the first 10,000 years after repository closure.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027 x 10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report* YMP-TR-004Q, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which was shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation.* ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are excluded from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined (CRWMS M&O 2000g, Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events, and Processes: Disruptive Events* ANL-WIS-MD-000005 REV 00 ICN 1: CRWMS M&O 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4) Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision is *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

Criticality in a waste package following partial damage due to igneous intrusion can be viewed as a special case of this FEP because the most likely partial damage, a rupture of the lid weld, has been conservatively modeled as if it were a top breach (CRWMS M&O 2000g, Section 6.2.1). With such an interpretation, the igneous intrusion part of this FEP is identical with the partial damage part of the FEP "Criticality in waste and EBS" (2.1.14.01.00). This FEP differs by having no loss of neutron absorber from the waste package at all. Therefore, the explanation given in FEP (2.1.14.01.00) applies here as well, so the internal criticality part is repeated here for clarity. Criticality following igneous disruption is examined in CRWMS M&O 2000g (Section 6.2) for water-moderated configurations in partially damaged packages. Under the very conservative assumption of loss of all added neutron absorber, the joint probability of igneous disruption and in-package criticality is calculated to be 1.8×10^{-7} (or 1.8 E-07) in 10,000 years (CRWMS M&O 2000g, Section 6.2.1).

The silica-moderated part of the igneous intrusion scenario of "Criticality in waste and EBS" (2.1.14.01.00) applies only to external criticality, and this FEP is concerned solely with internal criticality. Therefore, that portion of the (2.1.14.01.00) argument is not repeated here.

TSPA Disposition: In-situ criticality in the nominal configuration following a breach in the top of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure.

Supplemental Discussion: See Screening Argument

Related PMRs, AMRs, and Calculations: None

IRSR Issues: CLST 5

Related Primary FEPs:

Criticality in-situ, waste package internal structures degrade faster than waste form, top breach (2.1.14.03.00)

Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach (2.1.14.04.00)

Criticality in-situ, waste package internal structures degrade slower than waste form, top breach (2.1.14.05.00)

Criticality in-situ, waste form degrades in place and swells, top breach (2.1.14.06.00)

Criticality in-situ, bottom breach allows flow through waste package, fissile material collects at bottom of waste package (2.1.14.07.00)

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place (2.1.14.08.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Criticality-MPC flooded (2.1.14.02.01)

Relationship to Primary FEP: Redundant, retained in FEP list for completeness. Note that this FEP is specific to a type of package, the "Multi-Purpose Container."
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number: Criticality-nominal configuration, partially flooded, otherwise intact (2.1.14.02.02)

Relationship to Primary FEP: Partial flooding is addressed in the context of the Primary FEP through the consideration of water that enters the package through a top breach.
Screening and Disposition: Same as the Primary FEP

6.3.3 Criticality In-Situ, Waste Package Internal Structures Degrade Faster Than Waste Form, Top Breach (2.1.14.03.00)

FEP Description: The waste package internal structures degrade, but not the waste form. There is a breach near the top of the waste package, which allows standing water to collect in the waste package. Significant amounts of the neutron absorber are flushed out the top of the waste package and criticality occurs in-situ.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of DSNF following igneous intrusion).

Screening Argument: In-situ criticality in degraded configurations of the waste package internal structures following a breach in the top of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure. For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report* YMP-TR-004Q, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which was shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4), and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events, and Processes: Disruptive Events* ANL-WIS-MD-000005 REV 00 ICN 1: CRWMS M&O 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision is *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material

(CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

As with FEP 2.1.14.02.00, Criticality in a waste package following partial damage due to igneous intrusion can be viewed as a special case of this FEP. The reasoning for this FEP is even simpler than for FEP 2.1.14.02.00 because this FEP is just the special case of FEP 2.1.14.02.00 with the waste package internal structures degrading faster than the waste form. This assumption leads to loss of all added neutron absorber (boron from borated stainless steel in the case of CSNF, but the conservatism could apply to any waste form), which is precisely the assumption used in modeling the SNF case (CRWMS M&O 2000g, Section 6.2.1). Therefore, the explanation given in FEP "Criticality, in-situ, nominal configuration, top breach" (2.1.14.02.00) applies here as well, so the internal criticality part is repeated here for clarity. Criticality following igneous disruption is examined CRWMS M&O 2000g (Section 6.2) for water-moderated configurations in partially damaged packages. Under the very conservative assumption of loss of all added neutron absorber, the joint probability of igneous disruption and in-package criticality is calculated to be 1.8×10^{-7} (1.8 E-07) in 10,000 years (CRWMS M&O 2000g, Section 6.2.1).

The silica-moderated part of the igneous intrusion scenario of "Criticality in waste and EBS" (2.1.14.01.00) applies only to external criticality, and this FEP is concerned solely with internal criticality. Therefore, that portion of the (2.1.14.01.00) argument is not repeated here.

TSPA Disposition: In-situ criticality in degraded configurations of the waste package internal structures following a breach in the top of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events
ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: CLST 5

Related Primary FEPs:

Criticality in-situ, nominal configuration, top breach (2.1.14.02.00)

Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach (2.1.14.04.00)

Criticality in-situ, waste package internal structures degrade slower than waste form, top breach (2.1.14.05.00)

Criticality in-situ, waste form degrades in place and swells, top breach (2.1.14.06.00)

Criticality in-situ, bottom breach allows flow through waste package, fissile material collects at bottom of waste package (2.1.14.07.00)

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place (2.1.14.08.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Waste package internal structures degrade faster than waste form (2.1.14.03.01)

Relationship to Primary FEP: Redundant, retained in FEP list for completeness
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number: Waste package internal structures collapse (2.1.14.03.02)

Relationship to Primary FEP: Collapse of the internal structures is a subcategory of degradation of internal structures, and the FEP is, therefore, appropriately addressed in the broader context of the Primary FEP that addresses degradation of the internal structures.
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number: Criticality–container partially gone, optimal rod configuration, flooded (2.1.14.03.03)

Relationship to Primary FEP: Optimal fuel rod configuration in a flooded container could result from degradation of the internal structures, and this FEP is appropriately addressed in the context of the Primary FEP that addresses degradation of the internal structures. Optimal fuel rod configuration could also occur under other circumstances, and the secondary FEP could also have been mapped to Primary FEPs 2.1.14.04 and 2.1.14.07. Optimal configurations have been considered in the evaluation of all criticality FEPs, as appropriate.
Screening and Disposition: Same as the Primary FEP

6.3.4 Criticality In-Situ, Waste Package Internal Structures Degrade At Same Rate As Waste Form, Top Breach (2.1.14.04.00)

FEP Description: The waste package internal structures degrade at the same rate as the waste form. There is a breach near the top of the waste package, which allows water to collect in the waste package. Significant amounts of the neutron absorber are flushed out the top of the waste package. A slurry with insufficient neutron absorbing material forms at the waste package bottom and criticality occurs in-situ.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low Probability (Preliminary for criticality of DSNF following igneous intrusion).

Screening Argument: In-situ criticality in degraded configurations of the waste package internal structures and waste form following a breach in the top of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure. For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report* YMP-TR-004Q, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which was shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation*. ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events, and Processes: Disruptive Events*. ANL-WIS-MD-000005 REV 00 ICN 1: CRWMS M&O 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—*

Low consequence to dose Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision is *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP is similar to "Criticality, in-situ, waste package internal structures degrades faster than waste form, top breach" (2.1.14.03.00), but has the criticality control material (part of the internal structures) degrade at the same rate as the waste form. The screening argument for this FEP falls within the envelope of the argument for FEP (2.1.14.03.00) because the reference for that argument (CRWMS M&O 2000g, Section 6.2.1) conservatively assumed the loss of all added neutron absorber, which is certainly very unlikely when the waste form does not degrade slower than the waste package internal structures. Therefore, the explanation given in FEP (2.1.14.02.00) applies here as well, so the internal criticality part is repeated here for clarity. Criticality following igneous disruption is examined CRWMS M&O 2000g (Section 6.2) for water-moderated configurations in partially damaged packages. Under the very conservative assumption of loss of all added neutron absorber material, the joint probability of igneous disruption and in-package criticality is calculated to be 1.8×10^{-7} (or 1.8 E-07) in 10,000 years (CRWMS M&O 2000g, Section 6.2.1).

The silica-moderated part of the igneous intrusion scenario of "Criticality in waste and EBS" (2.1.14.01.00) applies only to external criticality, and this FEP is concerned solely with internal criticality. Therefore, that portion of the (2.1.14.01.00) argument is not repeated here.

TSPA Disposition: In-situ criticality in degraded configurations of the waste package internal structures and waste form following a breach in the top of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations: *Probability of Criticality Before 10,000 years*
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: CLST 5

Related Primary FEPs:

Criticality in-situ, nominal configuration, top breach (2.1.14.02.00)

Criticality in-situ, waste package internal structures degrade faster than waste form, top breach (2.1.14.03.00)

Criticality in-situ, waste package internal structures degrade slower than waste form, top breach (2.1.14.05.00)

Criticality in-situ, waste form degrades in place and swells, top breach (2.1.14.06.00)

Criticality in-situ, bottom breach allows flow through waste package, fissile material collects at bottom of waste package (2.1.14.07.00)

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place (2.1.14.08.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Waste package internal structures degrade at the same rate as the waste form (2.1.14.04.01)

Relationship to Primary FEP: Redundant, retained in FEP list for completeness
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number: Criticality – cladding and disintegrated pellets, optimally mixed, flooded (2.1.14.04.02)

Relationship to Primary FEP: Optimal mixtures of fuel pellets and cladding are possible following package breach and degradation of internal structures and waste form at the same rate, and this FEP is appropriately addressed in the context of the Primary FEP that addresses degradation of the internal structures and waste form. Optimal fuel rod configuration could also occur under other circumstances, and the secondary FEP could also have been mapped to other Primary FEPs, including

2.1.14.03 and 2.1.14.06. Optimal configurations have been considered in the evaluation of all criticality FEPs, as appropriate.

Screening and Disposition: Same as the Primary FEP

6.3.5 Criticality In-situ, Waste Package Internal Structures Degrade Slower Than Waste Form, Top Breach (2.1.14.05.00)

FEP Description: The waste package internal structures degrade slower than waste form. There is a breach near the top of the waste package, which allows water to collect in the waste package. The waste form degrades, separating from the neutron absorbers. A slurry forms at the waste package bottom and criticality occurs in-situ.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low Probability (Preliminary for criticality of DSNF following igneous intrusion).

Screening Argument: In-situ criticality in degraded configurations of the waste form following a breach in the top of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure. For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report* YMP-TR-004Q, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which was shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package* Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6*), the screening decision and basis f*or waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low* *consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP is similar to Criticality in-situ, waste package internal structures degrade faster than waste form, top breach" (2.1.14.03.00), but has the criticality control material (part of the internal structures) degrade at a slower rate than the waste form. The screening argument for this FEP falls within the envelope of the argument for FEP (2.1.14.03.00) because the reference for that argument, CRWMS M&O 2000, Section 6.2.1, conservatively assumed the loss of all added neutron absorber, which is certainly very unlikely when the waste form does not degrade more slowly than the waste package internal structures. Therefore, the explanation given in FEP (2.1.14.03.00) applies here as well, so the internal criticality part is repeated here for clarity. Criticality following igneous disruption is examined in CRWMS M&O 2000g (Section 6.2) for water-moderated configurations in partially damaged packages. Under the very conservative assumption of loss of all added neutron absorber material, the joint probability of igneous disruption and in-package criticality is calculated to be 1.8×10^{-7} (1.8 E-07) in 10,000 years (CRWMS M&O 2000g, Section 6.2.1).

The silica-moderated part of the igneous intrusion scenario of "Criticality in waste and EBS" (2.1.14.01.00) applies only to external criticality, and this FEP is concerned solely with internal criticality. Therefore, that portion of the (2.1.14.01.00) argument is not repeated here.

TSPA Disposition: In-situ criticality in degraded configurations of the waste form following a breach in the top of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations: *Probability of Criticality Before 10,000 years*
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: CLST 5

Related Primary FEPs:

Criticality in-situ, nominal configuration, top breach (2.1.14.02.00)

Criticality in-situ, waste package internal structures degrade faster than waste form, top breach (2.1.14.03.00)

Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach (2.1.14.04.00)

Criticality in-situ, waste form degrades in place and swells, top breach (2.1.14.06.00)

Criticality in-situ, bottom breach allows flow through waste package, fissile material collects at bottom of waste package (2.1.14.07.00)

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place (2.1.14.08.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Waste package internal structures degrade slower than the waste form (2.1.14.05.01)

Relationship to Primary FEP: Redundant, retained in FEP list for completeness
Screening and Disposition: Same as the Primary FEP

6.3.6 Criticality In-Situ, Waste Form Degrades In Place and Swells, Top Breach (2.1.14.06.00)

FEP Description: The waste package internal structures remain intact while the waste form degrades. There is a breach near the top of the waste package, which allows water to collect in the waste package. The waste form degrades in place, but swells into a more reactive configuration, which may overwhelm the in-place neutron absorbing material. Criticality occurs in-situ.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR—Low probability (Preliminary for criticality of DSNF following igneous intrusion)

Screening Argument: In-situ criticality in degraded configurations of the waste form following a breach in the top of the waste package has been *Excluded* from the TSPA–SR based on the low probability of occurrence during the first 10,000 years after repository closure.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package* Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12 see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN1: CRWMS 2000f, Section 6.2.6*), the screening decision and basis f*or waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose,* based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP differs from FEPS (2.1.14.03.00) through (2.1.14.05.00) in having only a small degree of separation of the waste form from the neutron absorber, and having no loss of neutron absorber from the waste package at all. The screening argument for this FEP falls within the envelope of the argument for FEP "Criticality in-situ, waste package internal structures degrade faster than waste form, top breach" (2.1.14.03.00) because the reference for that argument, (CRWMS M&O 2000g, Section 6.2.1), conservatively assumed the loss of all added neutron absorber. Therefore, the explanation given in FEP (2.1.14.03.00) applies here as well, so the internal criticality part is repeated here for clarity. Criticality following igneous disruption is examined in CRWMS M&O 2000g (Section 6.2) for water-moderated configurations in partially damaged packages. Under the very conservative assumption of loss of all added neutron absorber material, the joint probability of igneous disruption and in-package criticality is calculated to be 1.8×10^{-7} (1.8 E-07) in 10,000 years (CRWMS M&O 2000g, Section 6.2.1).

The silica-moderated part of the igneous intrusion scenario of "Criticality in waste and EBS" (2.1.14.01.00) applies only to external criticality, and this FEP is concerned solely with internal criticality. Therefore, that portion of the (2.1.14.01.00) argument is not repeated here.

TSPA Disposition: In-situ criticality in degraded configurations of the waste form following a breach in the top of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events
ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00
(CRWMS M&O 2000h)

IRSR Issues: CLST 5

Related Primary FEPs:

Criticality in-situ, nominal configuration, top breach (2.1.14.02.00)

Criticality in-situ, waste package internal structures degrade faster than waste form, top breach (2.1.14.03.00)

Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach (2.1.14.04.00)

Criticality in-situ, waste package internal structures degrade slower than waste form, top breach (2.1.14.05.00)

Criticality in-situ, bottom breach allows flow through waste package, fissile material collects at bottom of waste package (2.1.14.07.00)

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place (2.1.14.08.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.3.7 Criticality In-Situ, Bottom Breach Allows Flow Through Waste Package, Fissile Material Collects at Bottom of Waste Package (2.1.14.07.00)

FEP Description: There is a breach at the bottom of the waste package, which does not allow water to collect in the waste package. Moderation is provided by water retained in clay or hydrated metal corrosion products accumulating in the bottom of the waste package with the fissile material. Significant amounts of the neutron absorber are either flushed from the waste package or remain distributed throughout the waste package, while fissile material collects at bottom of the waste package. Criticality occurs in-situ.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of DSNF following igneous intrusion).

Screening Argument: In-situ criticality in following a breach in the bottom of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027 x 10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package* Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12 see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6*),* the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP differs from FEPs (2.1.14.03.00) through (2.1.14.05.00) by having penetration of the bottom of the waste package so that there is very little free water retained in the waste package. This leaves silica clay as the only moderator left in the waste package, and this is a much less efficient moderator than free water (CRWMS M&O 1999e, Section 6.2). It also differs by having the fissile material collect at the bottom of the waste package, which is a less favorable geometry for criticality than distributed throughout the waste package (except, possibly, for plutonium-239 or highly enriched uranium waste forms) (CRWMS M&O 1999f, Tables 6-1 through 6-5).

Therefore, the screening argument for this FEP falls within the envelope of the argument for FEP "Criticality in-situ, waste package internal structures degrade faster than waste form, top breach" (2.1.14.03.00), which considers the more efficient moderator of free water for a potential criticality assuming the same geometry. With this correspondence, the explanation given in FEP (2.1.14.03.00) applies here as well, so the internal criticality part is repeated here for clarity.

Criticality following igneous disruption is examined in CRWMS M&O 2000g (Section 6.2) for water-moderated configurations in partially damaged packages. Under the very conservative assumption of loss of all added neutron absorber material, the joint probability of igneous disruption and in-package criticality is calculated to be 1.8×10^{-7} (1.8 E-07) in 10,000 years (CRWMS M&O 2000g, Section 6.2.1).

The silica-moderated part of the igneous intrusion scenario of "Criticality in waste and EBS" (2.1.14.01.00) applies only to external criticality, and this FEP is concerned solely with internal criticality. Therefore, that portion of the (2.1.14.01.00) argument is not repeated here.

The *Exclude* screening decision is preliminary because calculations are incomplete for criticality of the DSNF waste forms that are also highly enriched following igneous disruption.

TSPA Disposition: In-situ criticality in following a breach in the bottom of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: CLST 5

Related Primary FEPs:

Criticality in-situ, nominal configuration, top breach (2.1.14.02.00)

Criticality in-situ, waste package internal structures degrade faster than waste form, top breach (2.1.14.03.00)

Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach (2.1.14.04.00)

Criticality in-situ, waste package internal structures degrade slower than waste form, top breach (2.1.14.05.00)

Criticality in-situ, waste form degrades in place and swells, top breach (2.1.14.06.00)

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place (2.1.14.08.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.3.8 Criticality In-Situ, Bottom Breach Allows Flow Through Waste Package, Waste Form Degrades In Place (2.1.14.08.00)

FEP Description: There is a breach at the bottom of the waste package, which does not allow water to collect in the waste package. Moderation is provided by water trapped in the clay or oxides. The waste form degrades in place and the neutron absorbing material mobilizes away from the waste form. Criticality occurs in-situ.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of DSNF following igneous intrusion).

Screening Argument: In-situ criticality in following a breach in the bottom of the waste package has been *Excluded* from the TSPA–SR based on low probability of occurrence during the first 10,000 years after repository closure.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of*

Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4), and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP differs from FEPs (2.1.14.03.00) through (2.1.14.05.00) by having penetration of the bottom of the waste package so that there is very little free water retained in the waste package. This leaves silica clay as the only moderator left in the waste package, and this is a much less efficient moderator than water (CRWMS M&O 1999e, Section 6.2). Unlike FEP (2.1.14.07.00), it has the fissile material distributed throughout the waste package, therefore, it completely falls within the screening argument for FEP "Criticality in-situ, waste package internal structures degrade faster than waste form, top breach" (2.1.14.03.00), without any need to exempt highly enriched or plutonium waste forms. With this correspondence, the explanation given in FEP (2.1.14.03.00) applies here as well, so the internal criticality part is repeated here for clarity. Criticality following igneous disruption is examined in CRWMS M&O 2000g (Section 6.2) for water-moderated configurations in partially damaged packages. Under the very conservative assumption of loss of all added neutron absorber material, the joint probability of igneous disruption and in-package criticality is calculated to be 1.8×10^{-7} (1.8 E-07) in 10,000 years (CRWMS M&O 2000g, Section 6.2.1).

The silica-moderated part of the igneous intrusion scenario of "Criticality in waste and EBS" (2.1.14.01.00) applies only to external criticality, and this FEP is concerned solely with internal criticality. Therefore, that portion of the (2.1.14.01.00) argument is not repeated here.

TSPA Disposition: In-situ criticality in CSNF in following a breach in the bottom of the waste package has been *Excluded* from the TSPA–SR based on the low probability of occurrence during the first 10,000 years after repository closure.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events
ANL-WIS-MD-000005 REV 00 ICN 1(CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: CLST 5

Related Primary FEPs:

Criticality in-situ, nominal configuration, top breach (2.1.14.02.00)

Criticality in-situ, waste package internal structures degrade faster than waste form, top breach (2.1.14.03.00)

Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach (2.1.14.04.00)

Criticality in-situ, waste package internal structures degrade slower than waste form, top breach (2.1.14.05.00)

Criticality in-situ, waste form degrades in place and swells, top breach (2.1.14.06.00)

Criticality in-situ, bottom breach allows flow through waste package, fissile material collects at bottom of waste package (2.1.14.07.00)

Treatment of Secondary FEPs:

<u>*Secondary FEP Name and Number:*</u> Neutron absorber system selectively degrades (2.1.14.08.01)

Relationship to Primary FEP: Selective degradation of the neutron absorber system could occur in-situ following a bottom breach that allows flow through the waste package, and this FEP is appropriately mapped to the Primary FEP that addresses this circumstance. Selective degradation of the neutron absorbers could also occur under other circumstances, and the secondary FEP could have been mapped to Primary FEPs (2.1.14.03.00), (2.1.14.04.00), (2.1.14.05.00), and (2.1.14.07.00). Selective degradation of the neutron absorber has been considered in the evaluation of all criticality FEPs, as appropriate.

Screening and Disposition: Same as the Primary FEP

<u>Secondary FEP Name and Number</u>: Neutron absorbers selectively flushed from container (2.1.14.08.02)

Relationship to Primary FEP: Selective flushing of the neutron absorbers could occur in-situ following a bottom breach that allows flow through the waste package, and this FEP is appropriately mapped to the Primary FEP that addresses this circumstance. Selective flushing of the neutron absorbers could also occur under other circumstances, and the secondary FEP could have been mapped to Primary FEPs (2.1.14.03.00), (2.1.14.04.00), (2.1.14.05.00), and (2.1.14.07.00). Selective flushing of the neutron absorber has been considered in the evaluation of all criticality FEPs, as appropriate.

Screening and Disposition: Same as the Primary FEP

<u>Secondary FEP Name and Number</u>: Selective leaching of neutron absorber (2.1.14.08.03)

Relationship to Primary FEP: Selective leaching is the same as selective flushing, so this FEP is exactly the same as the previous Secondary FEP, (2.1.14.08.02). Selective leaching of the neutron absorbers could occur in-situ following a bottom breach that allows flow through the waste package, and this FEP is appropriately mapped to the Primary FEP that addresses this circumstance. Selective leaching of the neutron absorbers could also occur under other circumstances, and the secondary FEP could have been mapped to Primary FEPs (2.1.14.03.00), (2.1.14.04.00), (2.1.14.05.00), and (2.1.14.07.00). Selective leaching of the neutron absorber has been considered in the evaluation of all criticality FEPs, as appropriate.

Screening and Disposition: Same as the Primary FEP

6.3.9 Near-Field Criticality, Fissile Material Deposited in Near-Field Pond (2.1.14.09.00)

FEP Description: Fissile material-bearing solution or intact fissile material is deposited in a near-field pond. Fissile material may migrate due to bottom-only breach of cask or due to massive structural failure of waste package. Near-field criticality can result if fissile material geometry represents critical configuration and sufficient water is present in pond.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous intrusion).

Screening Argument: Near-field criticality following migration of fissile material from a breached waste package to a pond on the floor of the drift (or elsewhere in the near field) has been *Excluded* from the TSPA–SR based on low probability.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose,* based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Near-field criticality following migration of fissile material from a breached waste package to a pond on the floor of the drift (or elsewhere in the near field) has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events
ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: ENFE 5

Related Primary FEPs:

Criticality in waste and EBS (2.1.14.01.00)

Critical assembly forms away from repository (2.2.14.01.00)

Near-field criticality, fissile solution flows into drift low point (2.1.14.10.00)

Near-field criticality, fissile solution is adsorbed or reduced in invert (2.1.14.11.00)

Near-field criticality, filtered slurry or colloidal stream collects on invert surface (2.1.14.12.00)

Near-field criticality associated with colloidal deposits (2.1.14.13.00)

Out-of-package criticality, fuel/magma mixture (2.1.14.14.00)

Treatment of Secondary FEPs:

<u>Secondary FEP Name and Number:</u> Criticality – container gone, intact rods, flooded (2.1.14.09.01)

Relationship to Primary FEP: No credible circumstances are identified in which the fuel rods remain fully intact following complete removal of the waste package, and this secondary FEP has therefore been addressed as a variant of the Primary FEP in which criticality occurs in ponded water in the near field following transport of waste from the breached package. This secondary FEP could also have been mapped to the Primary FEPs related to in-situ criticality (e.g., (2.1.14.03.00), but was assigned to this location because of the implication in the FEP name that the package was fully removed, and because the only plausible mechanism for flooding of fuel material following complete removal of packages is through near-field ponding. The screening decisions of near-field and in-situ criticality are unaffected by the mapping of this secondary FEP.

Screening and Disposition: Same as the Primary FEP

<u>Secondary FEP Name and Number:</u> Criticality – container gone, intact rods, dry (2.1.14.09.02)

Relationship to Primary FEP: No credible circumstances are identified in which the fuel rods remain fully intact following complete removal of the waste package, and this secondary FEP has, therefore, been addressed as a variant of the Primary FEP in which criticality occurs in ponded water in the near field following transport of waste from the breached package. Although the secondary FEP specifies that the fuel rods remain dry, criticality is not plausible in dry fuel material, and the FEP is, therefore, mapped to the most relevant credible Primary FEP. This secondary FEP could also have been mapped to the Primary FEPs related to in-situ criticality (e.g., (2.1.14.03.00), but was assigned to this location because of the implication in the FEP name that the package was fully removed. The screening decisions of near-field and in-situ criticality are unaffected by the mapping of this secondary FEP.

Screening and Disposition: Same as the Primary FEP

<u>Secondary FEP Name and Number:</u> Criticality – container gone, pile of fuel pellets, dry (2.1.14.09.03)

Relationship to Primary FEP: This secondary FEP has been addressed as a variant of the Primary FEP in which criticality occurs in ponded water in the near field following transport of waste from the breached package. Although the secondary FEP specifies that the fuel material remains dry, criticality is not plausible in dry fuel material, and the FEP is, therefore, mapped to the most relevant credible Primary FEP. This secondary FEP could also have been mapped to the Primary FEPs related to in-situ criticality (e.g., (2.1.14.03.00), but was assigned to this location because of the implication in the FEP name that the package was fully

removed. The screening decisions of near-field and in-situ criticality are unaffected by the mapping of this secondary FEP.
Screening and Disposition: Same as the Primary FEP

<u>Secondary FEP Name and Number:</u> Criticality – container gone, pile of fuel pellets, flooded (2.1.14.09.04)

Relationship to Primary FEP: This secondary FEP has been addressed as a variant of the Primary FEP in which criticality occurs in ponded water in the near field following transport of waste from the breached package. This secondary FEP could also have been mapped to the Primary FEPs related to in-situ criticality (e.g., (2.1.14.03.00), but was assigned to this location because of the implication in the FEP name that the package was fully removed. The screening decisions of near-field and in-situ criticality are unaffected by the mapping of this secondary FEP.
Screening and Disposition: Same as the Primary FEP

<u>Secondary FEP Name and Number:</u> Criticality – container and cladding gone, fuel powder, flooded (2.1.14.09.05)

Relationship to Primary FEP: This secondary FEP has been addressed as a variant of the Primary FEP in which criticality occurs in ponded water in the near field following transport of waste from the breached package. This secondary FEP could also have been mapped to the Primary FEPs related to in-situ criticality (e.g., (2.1.14.03.00), but was assigned to this location because of the implication in the FEP name that the package was fully removed. The screening decisions of near-field and in-situ criticality are unaffected by the mapping of this secondary FEP.
Screening and Disposition: Same as the Primary FEP

<u>Secondary FEP Name and Number:</u> Criticality – container and cladding gone, fuel powder, dry (2.1.14.09.06)

Relationship to Primary FEP: This secondary FEP has been addressed as a variant of the Primary FEP in which criticality occurs in ponded water in the near field following transport of waste from the breached package. Although the secondary FEP specifies that the fuel powder remains dry, criticality is not plausible in dry fuel material (CRWMS M&O 1999e, Section 6.2), and the FEP is, therefore, mapped to the most relevant credible Primary FEP. This secondary FEP could also have been mapped to the Primary FEPs related to in-situ criticality (e.g., (2.1.14.03.00), but was assigned to this location because of the implication in the FEP name that the package was fully removed. The screening decisions of near-field and in-situ criticality are unaffected by the mapping of this secondary FEP.
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number: Formation of a critical assembly in a pool (in waste and EBS) (2.1.14.09.07)

Relationship to Primary FEP: Redundant, retained for completeness
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number: Pu accumulates in basin pool (in waste and EBS) (2.1.14.09.08)

Relationship to Primary FEP: Redundant, retained for completeness. Plutonium-239 is one of the fissile radionuclides considered in criticality analyses.
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number Accumulated 239 Pu decays to 235 U in basin pool (in waste and EBS) (2.1.14.09.09)

Relationship to Primary FEP: Redundant, retained for completeness. Uranium-235 is one of the fissile radionuclides considered in criticality analyses.
Screening and Disposition: Same as the Primary FEP

6.3.10 Near-Field Criticality, Fissile Solution Flows into Drift Lowpoint (2.1.14.10.00)

FEP Description: Near-field criticality results when fissile material-bearing solution flows into a drift lowpoint. The poison has already been separated from the solution carrying the fissile material, either due to retention in intact components within the waste package or prior removal by flow-through leaching within the waste package.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Near-field criticality following migration of fissile material from a breached waste package to low point in the drift (or elsewhere in the near field) has been *Excluded* from the TSPA–SR based on low probability. With respect to breach of the waste package, this FEP is the same as "Near-field criticality, fissile material deposited in near field pond" (2.1.14.09.00). Therefore, the nominal performance breach probability for that FEP has been only slightly modified for inclusion here, as follows.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027 x 10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

With respect to external criticality, this FEP is similar to "Near-field criticality, fissile material deposited in near field pond" (2.1.14.09.00) except that there is a possibility of a drift low-point collecting fissile material from several waste packages, thereby making the accumulation of a critical mass more likely. Nevertheless, the following screening argument from FEP (2.1.14.09.00) is still relevant. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Near-field criticality following migration of fissile material from a breached waste package to low point in the drift (or elsewhere in the near field) has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: ENFE 5

Related Primary FEPs:

Near-field criticality, fissile material deposited in near field pond (2.1.14.09.00)

Near-field criticality, fissile solution is adsorbed or reduced in invert (2.1.14.11.00)

Near-field criticality, filtered slurry or colloidal stream collects on invert surface (2.1.14.12.00)

Near-field criticality associated with colloidal deposits (2.1.14.13.00)

Out-of-package criticality, fuel/magma mixture (2.1.14.14.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Accumulation of clays and sediments in basins (in EBS) (2.1.14.10.01)

Relationship to Primary FEP: To the extent that the secondary FEP refers to the possibility of criticality in sediments that contain radionuclides deposited from solution, it is a subcase of the Primary FEP. To the extent that the secondary FEP refers to deposition of fissile material transported as a solid, the FEP could have been mapped to the Primary FEP (2.1.14.09.00). The mapping is appropriate, and screening arguments for both FEPs (2.1.14.10.00) and (2.1.14.09.00) are unaffected by the mapping decision.

Screening and Disposition: Same as the Primary FEP

6.3.11 Near-Field Criticality, Fissile Solution is Adsorbed or Reduced In Invert (2.1.14.11.00)

FEP Description: Near-field criticality results from fissile solution adsorbed or reduced in invert (concrete and crushed tuff). The geometry of the invert allows zonal precipitation (under the influence of gravity) wherein the fissile and non fissile species may precipitate at different places within the invert.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Near-field criticality following migration of fissile material from a breached waste package to a location where it is adsorbed or reduced in the invert (or elsewhere in the near field) has been *Excluded* from the TSPA–SR based on low probability. With respect to breach of the waste package, this FEP is the same as "Near-field criticality, fissile material deposited in near field pond" (2.1.14.09.00). Therefore, the nominal performance breach probability for that FEP has been only slightly modified for inclusion here, as follows.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027 x 10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package* Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

With respect to critical configurations that can follow an igneous intrusion scenario, this FEP is the same as "Near-field criticality, fissile material deposited in near field pond" (2.1.14.09.00) except that the accumulation may be in a flatter geometry, which will be less favorable to criticality. Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.1.14.09.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Near-field criticality following migration of fissile material from a breached waste package to a location where it is adsorbed or reduced in the invert (or elsewhere in the near field) has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: ENFE 5

Related Primary FEPs:

Near-field criticality, fissile material deposited in near field pond (2.1.14.09.00)

Near-field criticality, fissile solution flows into drift low point (2.1.14.10.00)

Near-field criticality, filtered slurry or colloidal stream collects on invert surface (2.1.14.12.00)

Near-field criticality associated with colloidal deposits (2.1.14.13.00)

Out-of-package criticality, fuel/magma mixture (2.1.14.14.00)

Treatment of Secondary FEPs No Secondary FEPs

6.3.12 Near-Field Criticality, Filtered Slurry or Colloidal Stream Collects On Invert Surface (2.1.14.12.00)

FEP Description: Near-field criticality results when slurry or colloidal stream is filtered (i.e., neutron absorbers are removed) by waste package corrosion products and collect on top of invert surface.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Near-field criticality in the invert (or elsewhere in the near field) following migration of fissile material from a breached waste package and filtration of a slurry or colloidal stream of neutron absorbers has been *Excluded* from the TSPA–SR based on low probability. With respect to breach of the waste package, this FEP is the same as "Near-field criticality, fissile material deposited in near field pond" (2.1.14.09.00). Therefore, the nominal performance breach probability for that FEP has been only slightly modified for inclusion here, as follows.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package D*egradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined (CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose,* based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

With respect to critical configurations that can follow an igneous intrusion scenario, this FEP is the same as "Near-field criticality, fissile material deposited in near field ponds" (2.1.14.09.00) except that the accumulation will be in a much flatter geometry (invert surface), which will be less favorable to criticality. Hence, the conditions for the occurrence of criticality will be bounded. Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Near-field criticality in the invert (or elsewhere in the near field) following migration of fissile material from a breached waste package and filtration of a slurry or colloidal stream of neutron absorbers has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)
Features, Events, and Processes: Disruptive Events
ANL-WIS-MD-000005 REV 00 ICN 1(CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00
(CRWMS M&O 2000h)

IRSR Issues: ENFE 5

Related Primary FEPs:

Interaction with corrosion products (2.1.09.02.00)

Colloid filtration in the waste and EBS (2.1.09.20.00)

Near-field criticality, fissile material deposited in near field pond (2.1.14.09.00)

Near-field criticality, fissile solution flows into drift low point (2.1.14.10.00)

Near-field criticality, fissile solution is adsorbed or reduced in invert (2.1.14.11.00)

Near-field criticality associated with colloidal deposits (2.1.14.13.00)

Out-of-package criticality, fuel/magma mixture (2.1.14.14.00)

Treatment of Secondary FEPs — No Secondary FEPs

6.3.13 Near-Field Criticality Associated With Colloidal Deposits (2.1.14.13.00)

FEP Description: Near-field criticality could result from colloids deposited in fractured or degraded concrete, from colloids filtered in the invert, or from colloids deposited in dead-ends of stress-relief cracks in the surrounding tunnel.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Near-field criticality in the invert (or elsewhere in the near field) following migration of fissile material from a breached waste package and filtration or deposition of colloids containing fissile material has been *Excluded* from the TSPA–SR based on low probability. With respect to breach of the waste package this FEP is the same as "Near-field criticality, fissile material deposited in near field pond" (2.1.14.09.00). Therefore, the nominal performance breach probability for that FEP has been only slightly modified for inclusion here as follows.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027 x 10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002

REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

With respect to critical configurations that can follow an igneous intrusion scenario, this FEP is the same as "Near-field criticality, fissile material deposited in near field pond" (2.1.14.09.00) except that the accumulation will be in colloids filtered in the invert, or colloids deposited in dead-ends of stress-relief cracks in the surrounding tunnel. Such geometries generally be flatter than the more general geometry of FEP (2.1.14.09.00). Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.1.14.09.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Near-field criticality in the invert (or elsewhere in the near field) following migration of fissile material from a breached waste package and filtration or deposition of colloids containing fissile material has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: ENFE 5

Related Primary FEPs:

Colloid transport and sorption in the waste and EBS (2.1.09.19.00)

Colloid filtration in the waste and EBS (2.1.09.20.00)

Near-field criticality, fissile material deposited in near field pond (2.1.14.09.00)

Near-field criticality, fissile solution flows into drift low point (2.1.14.10.00)

Near-field criticality, fissile solution is adsorbed or reduced in invert (2.1.14.11.00)
Near-field criticality, filtered slurry or colloidal stream collects on invert surface (2.1.14.12.00)

Out-of-package criticality, fuel/magma mixture (2.1.14.14.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.3.14 Out-of-Package Criticality, Fuel/Magma Mixture (2.1.14.14.00)

FEP Description: Interaction between fuel and magma dilutes fissile material, excludes water, and minimizes its return. For criticality to occur, neutron absorbers must also be removed.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of DSNF)

Screening Argument: Criticality in a mixture of spent fuel and magma has been *Excluded* from the TSPA–SR based on impossibility. As described in the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g, Section 6.2.2), silica-moderated CSNF criticality in a spent-fuel/magma mixture is shown to be physically impossible (k_{eff} = 0.77) even for the extraordinarily conservative assumption that the complete contents of seven waste packages could be arranged in an optimally-spaced cubic lattice with all neutron absorbers removed. Criticality of CSNF in a fuel/magma mixture is, therefore, not a credible event, and the FEP is *Excluded* from the TSPA–SR based on low probability. The *Exclude* screening decision is preliminary because calculations are not complete for DSNF.

TSPA Disposition: Criticality in a mixture of spent fuel and magma has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations: *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

IRSR Issues: ENFE 5

Related Primary FEPs:

Magma interacts with waste (1.2.04.04.00)

Near-field criticality, fissile material deposited in near field pond (2.1.14.09.00)

Near-field criticality, fissile solution flows into drift low point (2.1.14.10.00)
Near-field criticality, fissile solution is adsorbed or reduced in invert (2.1.14.11.00)

Near-field criticality, filtered slurry or colloidal stream collects on invert surface (2.1.14.12.00)

Near-field criticality associated with colloidal deposits (2.1.14.13.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.3.15 Critical Assembly Forms Away From Repository (2.2.14.01.00)

FEP Description: Nuclear criticality requires a sufficient concentration and localized (critical) mass of fissile isotopes (e.g., U-235, Pu-239) and also the presence of neutron moderating materials (e.g., water) in a suitable geometry. Criticality is liable to be damped by the presence of neutron absorbing isotopes (e.g., Pu-240). Far-field criticality can occur if fissile material is transported away from the repository and then a critical mass accumulates in the presence of water. This FEP aggregates all mechanisms for far-field criticality into a single category. Specific processes that could produce far-field criticality are discussed in FEPs (2.2.14.02.00) through (2.2.14.08.00).

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Decision Basis: Low Probability

Screening Argument: Criticality following transport of fissile material away from the repository has been *Excluded* from the TSPA–SR based on low probability.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)),and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" 1.2.03.02.00 (1.2.03.02.00) (CRWMS M&O 2000f, DE FEPs AMR, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

With respect to critical configurations that can follow an igneous intrusion scenario, this FEP is the same as "Near-field criticality, fissile material deposited in near field pond" (2.1.14.09.00) except that the accumulation would be further away (in the far-field host rock as contrasted with the near-field drift). The additional spreading inherent in the greater distance from the source is likely to make the accumulation of a critical mass less probable. Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.1.14.09.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Criticality following transport of fissile material away from the repository has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Event
ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00
(CRWMS M&O 2000h)

IRSR Issues: RT 4

Related Primary FEPs:

Criticality in waste and EBS (2.1.14.01.00)

Far-field criticality, precipitation in organic reducing zone in or near water table (2.2.14.02.00)

Far-field criticality, sorption on clay/zeolite in TSbv (2.2.14.03.00)

Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ (2.2.14.04.00)

Far-field criticality, precipitation in perched water above TSbv (2.2.14.05.00)

Far-field criticality, precipitation in fractures of TSw rock (2.2.14.06.00)

Far-field criticality, dryout produces fissile salt in a perched water basin (2.2.14.07.00)

Far-field criticality associated with colloidal deposits (2.2.14.08.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Reconcentration (release/migration factors) (2.2.14.01.01)

Relationship to Primary FEP: To the extent that the secondary FEP refers to the possibility of criticality as a result of reconcentration of radionuclides away from the repository, it is included in the consideration of processes that must occur for criticality to occur away from the repository. Therefore, this secondary FEP is appropriately mapped to the general FEP characterizing criticality in the far-field. The secondary FEP applies to all far-field criticality FEPs and could also have been mapped to Primary FEPs (2.2.14.02.00)) through (2.2.14.08.00). The choice of mapping does not affect screening decisions, as the process is considered in the evaluation of all far-field criticality Primary FEPs.
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number: Reconcentration (release/migration factors) (2.2.14.01.02)

Relationship to Primary FEP: This FEP is fully redundant with Secondary FEP (2.1.14.01.01) and is retained in the FEP list for completeness.
Screening and Disposition: Same as the Primary FEP

<u>Secondary FEP Name and Number:</u> DOE SNF criticality far-field (radionuclide inventory impact) (2.2.14.01.03)

Relationship to Primary FEP: Changes in radionuclide inventory are a possible effect of criticality, and would be addressed in consequence analysis of criticality, if necessary. Criticality in DOE SNF is a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the far field.

Screening and Disposition: Same as the Primary FEP The screening argument for nominal performance for the Primary FEP is based on analyses of waste package performance that are valid for all waste forms. As noted in the screening argument for the primary FEP, the screening decision is preliminary for far-field criticality in DOE SNF following igneous disruption.

<u>Secondary FEP Name and Number:</u> DOE SNF criticality far-field (waste heat impact) (2.2.14.01.04)

Relationship to Primary FEP: Heat generation is one of the potential effects of criticality, and would be addressed in consequence analysis of criticality, if necessary. Criticality in DOE SNF is a subcategory of criticality, and this FEP is, therefore, appropriately addressed in the broader context of the primary FEP that addresses all types of criticality in the far field.

Screening and Disposition: Same as the Primary FEP. The screening argument for nominal performance for the Primary FEP is based on analyses of waste package performance that are valid for all waste forms. As noted in the screening argument for the primary FEP, the screening decision is preliminary for far-field criticality in DOE SNF following igneous disruption.

6.3.16 Far-field criticality, precipitation in organic reducing zone in or near water table (2.2.14.02.00)

FEP Description: Fissile material is transported to an organic reducing zone and precipitates in a geometrically favorable configuration in or near water table.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Criticality following transport of fissile material away from the repository and precipitation in an organic reducing zone has been *Excluded* from the TSPA–SR based on low probability. Criticality following transport of fissile material away from the repository has been *Excluded* from the TSPA–SR based on low probability.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7 × 10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027 x 10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7 × 10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose,* based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP is a specific case of the general external criticality FEP, "Critical assembly forms away from repository " (2.2.14.01.00). Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.2.14.01.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach(CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Criticality following transport of fissile material away from the repository and precipitation in an organic reducing zone has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events
ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: RT 4

Related Primary FEPs:

Critical Assembly Forms Away From Repository (2.2.14.01.00)

Far-field criticality, sorption on clay/zeolite in TSbv (2.2.14.03.00)

Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ (2.2.14.04.00)

Far-field criticality, precipitation in perched water above TSbv (2.2.14.05.00)

Far-field criticality, precipitation in fractures of TSw rock (2.2.14.06.00)

Far-field criticality, dryout produces fissile salt in a perched water basin (2.2.14.07.00)

Far-field criticality associated with colloidal deposits (2.2.14.08.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Precipitation of U at reducing zone associated with organics in alluvial aquifer (2.2.14.02.01)

Relationship to Primary FEP: This Secondary FEP is a subcase of the Primary FEP, and is appropriately mapped to it.
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number: Precipitation of U at reducing zone associated with organics in Franklin Lake Playa (2.2.14.02.02)

Relationship to Primary FEP: This Secondary FEP is a subcase of the Primary FEP, and is appropriately mapped to it.
Screening and Disposition: Same as the Primary FEP

6.3.17 Far-Field Criticality, Sorption On Clay/Zeolite In TSbv (2.2.14.03.00)

FEP Description: Fissile material is transported to Topopah Springs unit where it sorbs onto the clays and zeolites of the basal vitrophyre in a geometrically favorable configuration.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Criticality following transport of fissile material away from the repository and sorption onto clays and zeolites in the basal vitrophyre of the Topopah Springs Formation has been *Excluded* from the TSPA–SR based on low probability. Criticality following transport of fissile material away from the repository has been *Excluded* from the TSPA–SR based on low probability.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package* Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN01: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose,* based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP is a specific case of the general external criticality FEP, "Critical assembly forms away from repository" (2.2.14.01.00). Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.2.14.01.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is likely to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Criticality following transport of fissile material away from the repository and sorption onto clays and zeolites in the basal vitrophyre of the Topopah Springs Formation has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: RT 4

Related Primary FEPs:

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place (2.1.14.08.00).

Critical Assembly Forms Away From Repository (2.2.14.01.00)

Far-field criticality, precipitation in organic reducing zone in or near water table (2.2.14.02.00)

Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ (2.2.14.04.00)

Far-field criticality, precipitation in perched water above TSbv (2.2.14.05.00)

Far-field criticality, precipitation in fractures of TSw rock (2.2.14.06.00)

Far-field criticality, dryout produces fissile salt in a perched water basin (2.2.14.07.00)

Far-field criticality associated with colloidal deposits (2.2.14.08.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.3.18 Far-Field Criticality, Precipitation Caused By Hydrothermal Upwell or Redox Front in the SZ (2.2.14.04.00)

FEP Description: Fissile material is transported to the SZ where it encounters hydrothermal upwelling or a redox front and precipitates in a geometrically favorable configuration in the SZ.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Criticality following transport of fissile material away from the repository and precipitation in a hydrothermal upwelling or redox front has been *Excluded* from the TSPA–SR based on low probability. Criticality following transport of fissile material away from the repository has been *Excluded* from the TSPA–SR based on low probability.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which is shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4), and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose,* based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP is a specific case of the general external criticality FEP, "Critical assembly forms away from repository" (2.2.14.01.00). Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.2.14.01.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Criticality following transport of fissile material away from the repository and precipitation in a hydrothermal upwelling or redox front has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events
ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: RT 4

Related Primary FEPs:

Critical Assembly Forms Away From Repository (2.2.14.01.00)

Far-field criticality, precipitation in organic reducing zone in or near water table (2.2.14.02.00)

Far-field criticality, sorption on clay/zeolite in TSbv (2.2.14.03.00)

Far-field criticality, precipitation in perched water above TSbv (2.2.14.05.00)

Far-field criticality, precipitation in fractures of TSw rock (2.2.14.06.00)

Far-field criticality, dryout produces fissile salt in a perched water basin (2.2.14.07.00)

Far-field criticality associated with colloidal deposits (2.2.14.08.00)

Treatment of Secondary FEPs:

Secondary FEP Name and Number: Precipitation of U in the upwelling zone along some faults (2.2.14.04.01)

Relationship to Primary FEP: This Secondary FEP is a subcase of the Primary FEP, and is appropriately mapped to it.
Screening and Disposition: Same as the Primary FEP

Secondary FEP Name and Number: Precipitation of U below the redox front in the SZ (2.2.14.04.02)

Relationship to Primary FEP: This Secondary FEP is a subcase of the Primary FEP, and is appropriately mapped to it.
Screening and Disposition: Same as the Primary FEP

6.3.19 Far-Field Criticality, Precipitation in Perched Water Above TSbv (2.2.14.05.00)

FEP Description: Fissile material is transported to the perched water above the Topopah Springs basal vitrophyre, where chemical change causes it to precipitate in a geometrically favorable configuration.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption)

Screening Argument: Criticality following transport of fissile material away from the repository and precipitation in perched water above the Topopah Springs basal vitrophyre has been *Excluded* from the TSPA–SR based on low probability. Criticality following transport of fissile material away from the repository has been *Excluded* from the TSPA–SR based on low probability.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027 x 10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which was shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low* *consequence to dose,* based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP is a specific case of the general external criticality FEP, "Criticality forms away from repository" (2.2.14.01.00). Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.2.14.01.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Criticality following transport of fissile material away from the repository and precipitation in perched water above the Topopah Springs basal vitrophyre has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g).

Features, Events, and Processes: Disruptive Events. ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f).

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: RT 4

Related Primary FEPs:

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place" (2.1.14.08.00)

Critical Assembly Forms Away From Repository (2.2.14.01.00)

Far-field criticality, precipitation in organic reducing zone in or near water table (2.2.14.02.00)

Far-field criticality, sorption on clay/zeolite in TSbv (2.2.14.03.00)

Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ (2.2.14.04.00)

Far-field criticality, precipitation in fractures of TSw rock (2.2.14.06.00)

Far-field criticality, dryout produces fissile salt in a perched water basin (2.2.14.07.00)

Far-field criticality associated with colloidal deposits (2.2.14.08.00)

Treatment of Secondary FEPs:

<u>Secondary FEP Name and Number:</u> Accumulation of solute in topographic lows of the altered TSbv (2.2.14.05.01)

Relationship to Primary FEP: This Secondary FEP is a subcase of the Primary FEP, and is appropriately mapped to it. (*Note: This FEP has been identified as (2.2.14.03.01)) in Rev. 00 of the FEPs database [CRWMS M&O 2000]. The numbering used here reflects the more appropriate mapping to the Primary FEP where the process is potentially of the greatest significance.)*
Screening and Disposition: Same as the Primary FEP

6.3.20 Far-Field Criticality, Precipitation In Fractures of TSw Rock (2.2.14.06.00)

FEP Description: Fissile material is transported to Topopah Springs welded unit where it precipitates in a geometrically favorable configuration within the fractures.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Criticality following transport of fissile material away from the repository and precipitation in fractures in the Topopah Springs welded tuff has been *Excluded* from the TSPA–SR based on low probability. Criticality following transport of fissile material away from the repository has been *Excluded* from the TSPA–SR based on low probability.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which was shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package D*egradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose,* based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically-induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP is a specific case of the general external criticality FEP, "Critical assembly forms away from repository" (2.2.14.01.00). Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.2.14.01.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Criticality following transport of fissile material away from the repository and precipitation in fractures in the Topopah Springs welded tuff has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g).

Features, Events, and Processes: Disruptive Events ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: RT 4

Related Primary FEPs:

Critical Assembly Forms Away From Repository (2.2.14.01.00)

Far-field criticality, precipitation in organic reducing zone in or near water table (2.2.14.02.00)

Far-field criticality, sorption on clay/zeolite in TSbv (2.2.14.03.00)

Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ (2.2.14.04.00)

Far-field criticality, precipitation in perched water above TSbv (2.2.14.05.00)

Far-field criticality, dryout produces fissile salt in a perched water basin (2.2.14.07.00)

Far-field criticality associated with colloidal deposits (2.2.14.08.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.3.21 Far-Field Criticality, Dryout Produces Fissile Salt in a Perched Water Basin (2.14.07.00)

FEP Description: Fissile material is transported to a perched water basin. Dryout (evaporation exceeds infiltration) of the basin and the solution containing fissile material results in a fissile salt in a geometrically favorable configuration in the basin.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Criticality following transport of fissile material away from the repository to a perched water basin where evaporation produces a fissile salt has been *Excluded* from the TSPA–SR based on low probability. Criticality following transport of fissile material away from the repository has been *Excluded* from the TSPA–SR based on low probability.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027×10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which was shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package Degradation* ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN 1, CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose* Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose,* based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP is a specific case of the general external criticality FEP, "Critical assembly forms away from repository" (2.2.14.01.00). Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.2.14.01.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Criticality following transport of fissile material away from the repository to a perched water basin where evaporation produces a fissile salt has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events
ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: RT 4

Related Primary FEPs:

Critical Assembly Forms Away From Repository (2.2.14.01.00)

Far-field criticality, precipitation in organic reducing zone in or near water table (2.2.14.02.00)

Far-field criticality, sorption on clay/zeolite in TSbv (2.2.14.03.00)

Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ (2.2.14.04.00)

Far-field criticality, precipitation in perched water above TSbv (2.2.14.05.00)

Far-field criticality, precipitation in fractures of TSw rock (2.2.14.06.00)

Far-field criticality associated with colloidal deposits (2.2.14.08.00)

Treatment of Secondary FEPs: No Secondary FEPs

6.3.22 Far-Field Criticality Associated With Colloidal Deposits (2.2.14.08.00)

FEP Description: Far-field criticality could result from colloids deposited in clays/zeolites in TSbv or deposited in perched water above the relatively impermeable TSbv.

Screening Decision and Regulatory Basis: *Excluded* from the TSPA–SR (Preliminary)—Low probability (Preliminary for criticality of all waste forms following igneous disruption).

Screening Argument: Criticality following transport of fissile material away from the repository and deposition of fissile colloids has been *Excluded* from the TSPA–SR based on low probability. Criticality following transport of fissile material away from the repository has been *Excluded* from the TSPA–SR based on low probability.

For nominal performance, the calculation *Probability of Criticality Before 10,000 years* CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g Section 6.1) indicates that the probability of a breach of a single waste package in the repository is approximately 2.7×10^{-7} during the first 10,000 years of performance [Note: The probability in 10,000 years can be alternatively expressed as 2.7 E-07, 0.0027 x 10^{-4}, 0.0027 E-04, or as explained in Assumption 5.7 of this document, ANL-WIS-MD-000019, this is an approximate annual probability of 2.7×10^{-11} or 2.7 E-11]. Because all potentially critical configurations relevant to nominal performance are characterized by aqueous separation of the fissile material from the neutron absorber (*Disposal Criticality Analysis Methodology Topical Report YMP-TR-004Q*, REV 0: YMP 1998, Sections 3.1 and 3.2), criticality cannot occur under nominal conditions as long as the waste packages are intact and the waste is dry. The probability of criticality under nominal performance can be no higher during the first 10,000 years than the probability of waste package failure, which was shown to be less than one chance in 10,000 in the first 10,000 years. Note that this analysis of the probability of waste package failure (CRWMS M&O 2000g, Section 6.1) included consideration of premature failure due to initial manufacturing and welding flaws in waste packages. Other causes of premature failure of waste packages have been evaluated in *FEPS Screening of Processes and Issues in Drip Shield and Waste Package D*egradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h, Section 6.2.12: see the FEP "Juvenile and early failure of waste containers" (2.1.03.08.00)), and are *Excluded* from the TSPA based on low probability of occurrence.

Criticality following potential disruption during seismic events has been examined in CRWMS M&O 2000g (Section 5.4) and was shown to be no more likely than criticality under nominal performance. As described in the FEP "Seismic vibration causes container failure" (1.2.03.02.00) (*Features, Events and Processes: Disruptive Events* ANL-WIS-MD-00005 REV 00 ICN01: CRWMS 2000f, Section 6.2.6), the screening decision and basis for waste package and drip shield failure due to vibratory ground motion was *Excluded (Preliminary)—Low consequence to dose*. Although analyses to date are insufficient to rule out the possibility of any waste package damage due to seismic motion, the screening argument concluded that seismically-induced failure mechanisms that might lead to significant breaches of both the drip shield and waste package were not credible. Without breaches that allow water to flow into the packages, criticality will be no more likely following seismic disruption than during nominal performance (CRWMS M&O 2000g, Section 5.4). Similarly, damage to the waste package and drip shield from seismically-induced rockfall has been examined through the FEP "Rockfall (large block)" (2.1.07.01.00) and the screening decision was *Excluded (Preliminary)—Low consequence to dose*, based on the conclusion that the drip shield will not be breached (CRWMS M&O 2000f, Section 6.2.17). Without a mechanism for seismic disruptions to introduce significant amounts of water into the waste packages during the first 10,000 years, there will be no credible mechanism for the separation of the neutron absorber from the fissile material (CRWMS M&O 2000g, Section 1). Seismically induced criticality is, therefore, *Excluded* from the TSPA–SR based on low probability. Note, however, that this screening decision is based in large part on preliminary screening decisions for FEPs 1.2.03.02.00 and 2.1.07.01.00, and must be reevaluated when work supporting those FEPs is complete.

This FEP is a specific case of the general external criticality FEP, "Critical assembly forms away from repository" (2.2.14.01.00). Hence, the conditions for the occurrence of criticality will be bounded by those for FEP (2.2.14.01.00). Therefore, the igneous intrusion screening argument for that FEP has been slightly modified for inclusion here, as follows. Evaluations of near-field and far-field criticality following igneous disruption are not complete, and will involve further consideration of the probability and consequence of criticality outside the waste package following waste package breach (CRWMS M&O 2000i). However, the external accumulation of a critical mass following igneous intrusion will require the leaching of fissile material from the waste package (either partially damaged or extensively damaged) remaining after the intrusive event. Preliminary work indicates that the joint probability of an igneous event and this configuration criticality event is expected to be shown to be less than one chance in 10,000 in the first 10,000 years following repository closure, but the *Exclude* screening decision remains preliminary until work is complete.

TSPA Disposition: Criticality following transport of fissile material away from the repository and deposition of fissile colloids has been *Excluded* from the TSPA–SR based on low probability.

Supplemental Discussion: See Screening Argument.

Related PMRs, AMRs, and Calculations:

Probability of Criticality Before 10,000 years
CAL-EBS-NU-000014 REV 00 (CRWMS M&O 2000g)

Features, Events, and Processes: Disruptive Events
ANL-WIS-MD-000005 REV 00 ICN 1 (CRWMS M&O 2000f)

FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation ANL-EBS-PA-000002 REV 00 (CRWMS M&O 2000h)

IRSR Issues: RT 4

Related Primary FEPs:

Criticality in-situ, waste package internal structures degrade faster than waste form, top breach (2.1.14.03.00)

Criticality in-situ, waste package internal structures degrade slower than waste form, top breach (2.1.14.05.00).

Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place (2.1.14.08.00)

Critical Assembly Forms Away From Repository (2.2.14.01.00)

Far-field criticality, precipitation in organic reducing zone in or near water table (2.2.14.02.00)

Far-field criticality, sorption on clay/zeolite in TSbv (2.2.14.03.00)

Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ (2.2.14.04.00)

Far-field criticality, precipitation in perched water above TSbv (2.2.14.05.00)

Far-field criticality, precipitation in fractures of TSw rock (2.2.14.06.00)

Far-field criticality, dryout produces fissile salt in a perched water basin (2.2.14.07.00)

Treatment of Secondary FEPs: No Secondary FEPs

7. CONCLUSIONS

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 Document Input Reference System (DIRS) database. Section 7.1 address System-Level FEPs and Section 7.2 addressed the Criticality FEPs.

7.1 System-Level FEPs

Table 4 provides a summary of the System-Level FEP-screening decisions and the basis for *Exclude* decisions. Shaded FEPs are Primary; others are Secondary.

Table 4. Summary of System-Level FEPs Screening Decisions

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Timescales of Concern	(0.1.02.00.00)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Spatial Domain of Concern	(0.1.03.00.00)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Regulatory Requirements and Exclusions	(0.1.09.00.00)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Assessment basis FEP	(0.1.09.00.01)	*Excluded* from the TSPA–SR	By Regulation – specific to WIPP
Assessment basis FEP (atmospheric processes)	(0.1.09.00.02)	*Excluded* from the TSPA–SR	By Regulation – specific to WIPP
Model and Data Issues	(0.1.10.00.00)	*Included* in the TSPA–SR (excluding unmodeled design features)	Does not satisfy a screening criterion
Boundary conditions	(0.1.10.00.01)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Uncertainties (repository)	(0.1.10.00.02)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Correlation	(0.1.10.00.03)	*Included* in the TSPA–SR	Does not satisfy a screening criterion

Table 4. Summary of System-Level FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Uncertainties (geosphere)	(0.1.10.00.04)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Correlation	(0.1.10.00.05)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Uncertainties (biosphere)	(0.1.10.00.06)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Model and data issues	(0.1.10.00.07)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Unmodeled design features	(0.1.10.00.08)	*Excluded* from the TSPA–SR	Low consequence to dose
Disposal geometry	(0.1.10.00.09)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Conceptual model hydrology	(0.1.10.00.10)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Correlation (contaminant speciation and solubility)	(0.1.10.00.11)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Records and Markers, Repository	(1.1.05.00.00)	*Included* for construction of markers to inform future humans of the location and contents of the repository, retention of records, and for lack of knowledge of the repository at future times / *Excluded* from the TSPA–SR for efficacy of markers and record retention to prevent intrusion after 100-years postclosure period.	Does not satisfy a screening criterion / By Regulation
Loss of Records	(1.1.05.00.01)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Repository records, markers	(1.1.05.00.02)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Loss of records	(1.1.05.00.03)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Loss of records	(1.1.05.00.04)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Repository Design	(1.1.07.00.00)	*Included* in the TSPA–SR for licensed repository design and for design modifications/ *Excluded* from the TSPA–SR for significant undetected deviations from design / *Excluded* for inadequacy or lack of safety of the proposed design and for non-YMP design elements.	Does not satisfy a screening criterion / Low consequence to dose / By Regulation
Poorly designed repository	(1.1.07.00.01)	*Excluded* from the TSPA–SR	Low consequence to dose and By Regulation
Design modification	(1.1.07.00.02)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
HLW panels (siting)	(1.1.07.00.03)	*Excluded* from the TSPA–SR	By Regulation – not a design element
TRU silos (siting)	(1.1.07.00.04)	*Excluded* from the TSPA–SR	By Regulation – not a design element

Table 4. Summary of System-Level FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Access tunnels and shafts	(1.1.07.00.05)	*Excluded* from the TSPA–SR	By Regulation – not a design element
Design and construction FEPs	(1.1.07.00.06)	*Excluded* from the TSPA–SR	Low consequence to dose and By Regulation
Design and construction	(1.1.07.00.07)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Design and construction FEPs	(1.1.07.00.08)	*Excluded* from the TSPA–SR	Low consequence to dose and By Regulation
Quality Control	(1.1.08.00.00)	*Included* in the TSPA–SR for Primary FEP and for Secondary FEPs (1.1.08.00.05) and (1.1.08.00.06) / *Excluded* from the TSPA–SR for Secondary FEPs addressing material defects, faulty fabrication and faulty or non-design standard construction) / *Excluded* from the TSPA–SR for Secondary FEPs addressing the installation of panel, silos, and drains)	Does not satisfy a screening criterion / Low consequence to dose/ By Regulation
Poorly constructed repository	(1.1.08.00.01)	*Excluded* from the TSPA–SR	Low consequence to dose
Material defects	(1.1.08.00.02)	*Excluded* from the TSPA–SR	Low consequence to dose
Common cause failures	(1.1.08.00.03)	*Excluded* from the TSPA–SR	Low consequence to dose
Poor quality construction	(1.1.08.00.04)	*Excluded* from the TSPA–SR	Low consequence to dose
Quality control	(1.1.08.00.05)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Quality control	(1.1.08.00.06)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Drains, installed to divert water around containers are improperly placed	(1.1.08.00.07)	*Excluded* from the TSPA–SR	By Regulation – not a design element
Schedule and Planning	(1.1.09.00.00)	*Excluded* from the TSPA–SR	By Regulation
Effects of phased operation	(1.1.09.00.01)	*Excluded* from the TSPA–SR	By Regulation

Table 4. Summary of System-Level FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Administrative Control, Repository Site	(1.1.10.00.00)	*Included* in the TSPA–SR for administrative control during preclosure period, for initial construction of markers and archiving of records, and for subsequent loss of administrative control / *Excluded* from the TSPA–SR for efficacy of administrative controls beyond 100-years of the postclosure period	Does not satisfy a screening criterion / By Regulation, a human-intrusion scenario must be considered regardless of the status of administrative control
Planning restrictions	(1.1.10.00.01)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Monitoring of Repository	(1.1.11.00.00)	*Excluded* from the TSPA–SR for monitoring operations / *Included* in the TSPA–SR monitoring wells and boreholes within the human-intrusion scenario	Low consequence to dose / Does not satisfy a screening criterion
Monitoring and remedial activities	(1.1.11.00.01)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Postclosure monitoring	(1.1.11.00.02)	*Excluded* from the TSPA–SR	Low consequence to dose
Post-closure monitoring	(1.1.11.00.03)	*Excluded* from the TSPA–SR	Low consequence to dose
Postclosure monitoring	(1.1.11.00.04)	*Excluded* from the TSPA–SR	Low consequence to dose
Accidents and Unplanned Events During Operation	(1.1.12.01.00)	*Excluded* from the TSPA–SR	Low consequence to dose
Preclosure events	(1.1.12.01.01)	*Excluded* from the TSPA–SR	Low consequence to dose
Sabotage and improper operation	(1.1.12.01.02)	*Excluded* from the TSPA–SR	By Regulation
Accidents during operation	(1.1.12.01.03)	*Excluded* from the TSPA–SR	Low consequence to dose
Accidents during operation	(1.1.12.01.04)	*Excluded* from the TSPA–SR	Low consequence to dose
Handling accidents	(1.1.12.01.05)	*Excluded* from the TSPA–SR	Low consequence to dose
Oil or organic fluid spill	(1.1.12.01.06)	*Excluded* from the TSPA–SR	Low consequence to dose
Retrievability	(1.1.13.00.00)	*Included* in the TSPA–SR for Primary and Secondary FEPs related to design elements and emplacement / *Excluded* from the TSPA–SR for operational and administrative considerations	Does not satisfy a screening criterion / By Regulation
Retrievability	(1.1.13.00.01)	*Excluded* from the TSPA–SR	By Regulation
Metamorphism	(1.2.05.00.00)	*Excluded* from the TSPA–SR	Low consequence to dose
Metamorphic activity	(1.2.05.00.01)	*Excluded* from the TSPA–SR	Low consequence to dose

Table 4. Summary of System-Level FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Regional metamorphism	(1.2.05.00.02)	*Excluded* from the TSPA–SR	Low consequence to dose
Metamorphic activity	(1.2.05.00.03)	*Excluded* from the TSPA–SR	Low consequence to dose
Metamorphic activity	(1.2.05.00.04)	*Excluded* from the TSPA–SR	Low consequence to dose
Diagenesis	(1.2.08.00.00)	*Excluded* from the TSPA–SR	Low consequence to dose
Diagenesis	(1.2.08.00.01)	*Excluded* from the TSPA–SR	Low consequence to dose
Diagenesis	(1.2.08.00.02)	*Excluded* from the TSPA–SR	Low consequence to dose
Fracture infills	(1.2.08.00.03)	*Excluded* from the TSPA–SR	Low consequence to dose
Diagenesis	(1.2.08.00.04)	*Excluded* from the TSPA–SR	Low consequence to dose
Salt Diapirism and Dissolution	(1.2.09.00.00)	*Excluded* from the TSPA SR	By Regulation and Low consequence to dose
Diapirism	(1.2.09.01.00)	*Excluded* from the TSPA–SR	By Regulation (for salt diapirism) and Low consequence to dose (for igneous diapirism)
Diapirism	(1.2.09.01.01)	*Excluded* from the TSPA–SR	By Regulation
Salt deformation	(1.2.09.01.02)	*Excluded* from the TSPA–SR	By Regulation
Diapirism	(1.2.09.01.03)	*Excluded* from the TSPA–SR	By Regulation
Deliberate Human Intrusion	(1.4.02.01.00)	*Excluded* from the TSPA SR for Deliberate Intrusion / *Included* in the TSPA–SR for a stylized human intrusion scenario.	By Regulation / Does not satisfy a screening criterion
Chemical sabotage	(1.4.02.01.01)	*Excluded* from the TSPA–SR	By Regulation
Waste retrieval, mining	(1.4.02.01.02)	*Excluded* from the TSPA–SR	By Regulation
Archeological intrusion	(1.4.02.01.03)	*Excluded* from the TSPA–SR	By Regulation
Recovery of repository materials	(1.4.02.01.04)	*Excluded* from the TSPA–SR	By Regulation
Malicious intrusion	(1.4.02.01.05)	*Excluded* from the TSPA–SR	By Regulation
Archaeological investigation	(1.4.02.01.06)	*Excluded* from the TSPA–SR	By Regulation
Deliberate intrusion	(1.4.02.01.07)	*Excluded* from the TSPA–SR	By Regulation
Malicious intrusion	(1.4.02.01.08)	*Excluded* from the TSPA–SR	By Regulation
Deliberate drilling intrusion	(1.4.02.01.09)	*Excluded* from the TSPA–SR	By Regulation
Archeological investigations	(1.4.02.01.10)	*Excluded* from the TSPA–SR	By Regulation

Table 4. Summary of System-Level FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Post-closure surface activities (intrusion)	(1.4.02.01.11)	*Excluded* from the TSPA–SR	By Regulation
Intrusion into accumulation zone in biosphere	(1.4.02.01.12)	*Excluded* from the TSPA–SR	By Regulation
Unsuccessful attempt at site improvement	(1.4.02.01.13)	*Excluded* from the TSPA–SR	By Regulation
Sabotage	(1.4.02.01.14)	*Excluded* from the TSPA–SR	By Regulation
Sabotage	(1.4.02.01.15)	*Excluded* from the TSPA–SR	By Regulation
Sudden energy release (in waste and EBS)	(1.4.02.01.16)	*Excluded* from the TSPA–SR	By Regulation
Other future uses of crystalline rock	(1.4.02.01.17)	*Excluded* from the TSPA–SR	By Regulation
Intrusion (human)	(1.4.02.01.18)	*Excluded* from the TSPA–SR	By Regulation
Inadvertent Human Intrusion	(1.4.02.02.00)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Accidental intrusion	(1.4.02.02.01)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Unintrusive Site Investigation	(1.4.03.00.00)	*Excluded* from the TSPA–SR	Low consequence to dose
Drilling Activities (Human Intrusion)	(1.4.04.00.00)	*Included* in the TSPA–SR for stylized drilling scenario / *Excluded* from the TSPA–SR for specific types of drilling scenarios	Does not satisfy a screening criterion / By Regulation
Geothermal	(1.4.04.00.01)	*Excluded* from the TSPA–SR	By Regulation
Other resources	(1.4.04.00.02)	*Excluded* from the TSPA–SR	By Regulation
Enhanced oil and gas recovery	(1.4.04.00.03)	*Excluded* from the TSPA–SR	By Regulation
Liquid waste disposal	(1.4.04.00.04)	*Excluded* from the TSPA–SR	By Regulation
Hydrocarbon storage	(1.4.04.00.05)	*Excluded* from the TSPA–SR	By Regulation
Exploratory drilling for hydrocarbons	(1.4.04.00.06)	*Excluded* from the TSPA–SR	By Regulation
Exploratory drilling for metals	(1.4.04.00.07)	*Excluded* from the TSPA–SR	By Regulation
Boreholes – exploration	(1.4.04.00.08)	*Excluded* from the TSPA–SR	By Regulation
Injection of liquid waste	(1.4.04.00.09)	*Excluded* from the TSPA–SR	By Regulation
Exploratory drilling	(1.4.04.00.10)	*Excluded* from the TSPA–SR	By Regulation
Exploitation drilling	(1.4.04.00.11)	*Excluded* from the TSPA–SR	By Regulation
Exploratory drilling	(1.4.04.00.12)	*Excluded* from the TSPA–SR	By Regulation
Geothermal exploitation	(1.4.04.00.13)	*Excluded* from the TSPA–SR	By Regulation
Liquid waste injection	(1.4.04.00.14)	*Excluded* from the TSPA–SR	By Regulation

Table 4. Summary of System-Level FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Oil and gas exploration	(1.4.04.00.15)	*Excluded* from the TSPA–SR	By Regulation
Potash exploration	(1.4.04.00.16)	*Excluded* from the TSPA–SR	By Regulation
Water resource exploration	(1.4.04.00.17)	*Excluded* from the TSPA–SR	By Regulation
Oil and gas exploration	(1.4.04.00.18)	*Excluded* from the TSPA–SR	By Regulation
Groundwater exploitation	(1.4.04.00.19)	*Excluded* from the TSPA–SR	By Regulation
Geothermal energy production	(1.4.04.00.20)	*Excluded* from the TSPA–SR	By Regulation
Geothermal energy production	(1.4.04.00.21)	*Excluded* from the TSPA–SR	By Regulation
Borehole – well	(1.4.04.00.22)	*Excluded* from the TSPA–SR	By Regulation
Reuse of boreholes	(1.4.04.00.23)	*Excluded* from the TSPA–SR	By Regulation
Oil and Gas extraction	(1.4.04.00.24)	*Excluded* from the TSPA–SR	By Regulation
Liquid waste disposal	(1.4.04.00.25)	*Excluded* from the TSPA–SR	By Regulation
Enhanced oil and gas production	(1.4.04.00.26)	*Excluded* from the TSPA–SR	By Regulation
Hydrocarbon storage	(1.4.04.00.27)	*Excluded* from the TSPA–SR	By Regulation
Effects of Drilling Intrusion	(1.4.04.01.00)	*Included* in the TSPA–SR for interactions and changes in conditions/*Excluded* from the TSPA–SR for materials brought to the surface	Does not satisfy a screening criterion / By Regulation
Drilling fluid interacts with waste	(1.4.04.01.01)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Drilling introduces surfactants	(1.4.04.01.02)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Direct exposure to waste in mud pit	(1.4.04.01.03)	*Excluded* from the TSPA–SR	By Regulation
Flooding of drifts with drilling fluids	(1.4.04.01.04)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Drilling fluid flow	(1.4.04.01.05)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Drilling fluid loss	(1.4.04.01.06)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Blowouts	(1.4.04.01.07)	*Included in* the TSPA–SR	Does not satisfy a screening criterion
Drilling-induced geochemical changes	(1.4.04.01.08)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Fluid injection-induced geochemical changes	(1.4.04.01.09)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Cuttings	(1.4.04.01.10)	*Excluded* from the TSPA–SR	By Regulation
Cavings	(1.4.04.01.11)	*Excluded* from the TSPA–SR	By Regulation
Spallings	(1.4.04.01.12)	*Excluded* from the TSPA–SR	By Regulation

Table 4. Summary of System-Level FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Mining and Other Underground Activities (Human Intrusion)	(1.4.05.00.00)	*Excluded* from the TSPA–SR	By Regulation
Mine shaft intersects waste container	(1.4.05.00.01)	*Excluded* from the TSPA–SR	By Regulation
A mine shaft creates a preferential path through the upper non-welded unit and a wetter zone develops	(1.4.05.00.02)	*Excluded* from the TSPA–SR	By Regulation
Intrusion (mining)	(1.4.05.00.03)	*Excluded* from the TSPA–SR	By Regulation
Mines	(1.4.05.00.04)	*Excluded* from the TSPA–SR	By Regulation
Solution mining	(1.4.05.00.05)	*Excluded* from the TSPA–SR	By Regulation
Water from mining above the repository drains through the repository	(1.4.05.00.06)	*Excluded* from the TSPA–SR	By Regulation
Underground dwellings	(1.4.05.00.07)	*Excluded* from the TSPA–SR	By Regulation
Resource mining	(1.4.05.00.08)	*Excluded* from the TSPA–SR	By Regulation
Tunneling	(1.4.05.00.09)	*Excluded* from the TSPA–SR	By Regulation
Underground construction	(1.4.05.00.10)	*Excluded* from the TSPA–SR	By Regulation
Quarrying, near surface extraction	(1.4.05.00.11)	*Excluded* from the TSPA–SR	By Regulation
Mining activities	(1.4.05.00.12)	*Excluded* from the TSPA–SR	By Regulation
Potash mining	(1.4.05.00.13)	*Excluded* from the TSPA–SR	By Regulation
Other resources	(1.4.05.00.14)	*Excluded* from the TSPA–SR	By Regulation
Tunneling	(1.4.05.00.15)	*Excluded* from the TSPA–SR	By Regulation
Construction of underground facilities	(1.4.05.00.16)	*Excluded* from the TSPA–SR	By Regulation
Archaeological excavations	(1.4.05.00.17)	*Excluded* from the TSPA–SR	By Regulation
Deliberate mining intrusion	(1.4.05.00.18)	*Excluded* from the TSPA–SR	By Regulation
Heat storage in lakes or underground	(1.4.05.00.19)	*Excluded* from the TSPA–SR	By Regulation
Changes in groundwater flow due to mining	(1.4.05.00.20)	*Excluded* from the TSPA–SR	By Regulation
Changes in geochemistry due to mining	(1.4.05.00.21)	*Excluded* from the TSPA–SR	By Regulation
Explosions and Crashes (Human Activities)	(1.4.11.00.00)	*Excluded* from the TSPA–SR	By Regulation
Bomb blast	(1.4.11.00.01)	*Excluded* from the TSPA–SR	By Regulation
Collisions, explosions, and impacts	(1.4.11.00.02)	*Excluded* from the TSPA–SR	By Regulation
Underground test of nuclear devices	(1.4.11.00.03)	*Excluded* from the TSPA–SR	By Regulation
Explosions	(1.4.11.00.04)	*Excluded* from the TSPA–SR	By Regulation

Table 4. Summary of System-Level FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Nuclear War	(1.4.11.00.05)	*Excluded* from the TSPA–SR	By Regulation
Underground nuclear testing	(1.4.11.00.06)	*Excluded* from the TSPA–SR	By Regulation
Explosions for resource recovery	(1.4.11.00.07)	*Excluded* from the TSPA–SR	By Regulation
Underground nuclear device testing	(1.4.11.00.08)	*Excluded* from the TSPA–SR	By Regulation
Changes in groundwater flow due to explosions	(1.4.11.00.09)	*Excluded* from the TSPA–SR	By Regulation
Meteorite Impact	(1.5.01.01.00)	*Excluded* from the TSPA–SR for direct exhumation, and direct fracturing to the repository horizon / *Excluded* from the TSPA–SR for alteration of flow paths, fracturing of overlying geologic units, and for changes in rock stress.	Low probability / Low consequence to dose
Meteorite impact	(1.5.01.01.01)	*Excluded* from the TSPA–SR	Low consequence to dose
Meteorite	(1.5.01.01.02)	*Excluded* from the TSPA–SR	Low probability
Meteorite Impact	(1.5.01.01.03)	*Excluded* from the TSPA–SR	Low probability
Impact of a large meteorite	(1.5.01.01.04)	*Excluded* from the TSPA–SR	Low probability
Extraterrestrial Events	(1.5.01.02.00)	*Excluded* from the TSPA–SR	Low consequence to dose
Changes in the Earth's Magnetic Field	(1.5.03.01.00)	*Excluded* from the TSPA–SR	Low consequence to dose
Flipping of the earth's magnetic poles	(1.5.03.01.01)	*Excluded* from the TSPA–SR	Low consequence to dose
Changes of the magnetic field	(1.5.03.01.02)	*Excluded* from the TSPA–SR	Low consequence to dose
Magnetic pole reversal	(1.5.03.01.03)	*Excluded* from the TSPA–SR	Low consequence to dose
Earth Tides	(1.5.03.02.00)	*Excluded* from the TSPA–SR	Low consequence to dose
Salt Creep	(2.2.06.05.00)	*Excluded* from the TSPA–SR	By Regulation
Effects of Repository Heat on the Biosphere	(2.3.13.03.00)	*Excluded* from the TSPA–SR	Low consequence to dose
Atmospheric Transport of Contaminants	(3.2.10.00.00)	*Included* in the TSPA–SR for transport mechanisms and species (via ashfall) / *Excluded* from the TSPA–SR for volatile radionuclides as a gaseous release through the host rock	Does not satisfy a screening criterion / Low consequence to dose
Suspension in air	(3.2.10.00.01)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Wind	(3.2.10.00.02)	*Included* in the TSPA–SR	Does not satisfy a screening criterion

Table 4. Summary of System-Level FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Radionuclide volatilization / aerosol/ dust production	(3.2.10.00.03)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Convection, turbulence, and diffusion (atmospheric)	(3.2.10.00.04)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Deposition (atmospheric)	(3.2.10.00.05)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Saltation	(3.2.10.00.06)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Atmosphere	(3.2.10.00.07)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Precipitation (meteoric)	(3.2.10.00.08)	*Included* in the TSPA–SR	Does not satisfy a screening criterion
Toxicity of Mined Rock	(3.3.06.01.00)	*Excluded* from the TSPA–SR	By Regulation

7.2 Criticality FEPs

Table 5 provides a summary of the Criticality FEPs screening decisions and the basis for *Excluded* from the TSPA decisions. Shaded FEPs are Primary; others are Secondary.

Table 5. Summary of Criticality FEPs Screening Decision

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Criticality in waste and EBS	(2.1.14.01.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality (in waste and EBS)	(2.1.14.01.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality (in waste and EBS)	(2.1.14.01.02)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Nuclear Criticality (in waste and EBS)	(2.1.14.01.03)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Nuclear Criticality (in waste and EBS)	(2.1.14.01.04)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Nuclear Criticality (in waste and EBS)	(2.1.14.01.05)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Nuclear Criticality: heat (in waste and EBS)	(2.1.14.01.06)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Nuclear explosions (in waste and EBS)	(2.1.14.01.07)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
DOE SNF criticality in-situ	(2.1.14.01.08)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
DOE SNF criticality in-situ (radionuclide inventory impact)	(2.1.14.01.09)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
DOE SNF criticality near-field (radionuclide inventory impact)	(2.1.14.01.10)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
DOE SNF criticality in-situ (waste heat impact)	(2.1.14.01.11)	*Excluded* from the TSPA–SR (Preliminary)	Low probability

Table 5. Summary of Criticality FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
DOE SNF criticality in-situ (waste package degradation impact)	(2.1.14.01.12)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
DOE SNF criticality in-situ (waste form degradation impact)	(2.1.14.01.13)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
DOE SNF criticality in-situ (cladding degradation impact)	(2.1.14.01.14)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Differential solubility of neutron poisons	(2.1.14.01.15)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Selective leaching of fissile materials	(2.1.14.01.16)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Differential solubility of fissile isotopes	(2.1.14.01.17)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality in-situ, nominal configuration, top breach	(2.1.14.02.00)	*Excluded* from the TSPA–SR	Low probability
Criticality – MPC flooded	(2.1.14.02.01)	*Excluded* from the TSPA–SR	Low probability
Criticality – nominal configuration, partially flooded, otherwise intact	(2.1.14.02.02)	*Excluded* from the TSPA–SR	Low probability
Criticality in-situ, waste package internal structures degrade faster than waste form, top breach	(2.1.14.03.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Waste package internal structures degrade faster than waste form	(2.1.14.03.01)	*Excluded* from the TSPA–SR	Low probability
Waste package internal structures collapse	(2.1.14.03.02)	*Excluded* from the TSPA–SR	Low probability
Criticality – container partially gone, optimal rod configuration, flooded	(2.1.14.03.03)	*Excluded* from the TSPA–SR	Low probability
Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach	(2.1.14.04.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Waste package internal structures and the waste form degrade at the same rate	(2.1.14.04.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality – clad and disintegrated pellets, optimally mixed, flooded	(2.1.14.04.02)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality in-situ, waste package internal structures degrade slower than waste form, top breach	(2.1.14.05.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Waste package internal structures degrade slower than waste form	(2.1.14.05.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality in-situ, waste form degrades in place and swells, top breach	(2.1.14.06.00)	*Excluded* from the TSPA–SR	Low probability
Criticality in-situ, bottom breach allows flow through waste package, fissile material collects at bottom of waste package	(2.1.14.07.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality in-situ, bottom breach allows flow through waste package, waste form degrades in place	(2.1.14.08.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Neutron absorber system selectively degrades	(2.1.14.08.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Neutron absorbers selectively flushed from containers	(2.1.14.08.02)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Selective leaching of neutron absorbers	(2.1.14.08.03)	*Excluded* from the TSPA–SR (Preliminary)	Low probability

Table 5. Summary of Criticality FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Near-field criticality, fissile material deposited in near field pond	(2.1.14.09.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality – container gone, intact rods, flooded	(2.1.14.09.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality – container gone, intact rods, dry	(2.1.14.09.02)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality – container gone, pile of fuel pellets, dry	(2.1.14.09.03)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality – container gone, pile of fuel pellets, flooded	(2.1.14.09.04)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality – container and cladding gone, fuel powder, flooded	(2.1.14.09.05)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Criticality – container and cladding gone, pile of fuel pellets, dry	(2.1.14.09.06)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Formation of a critical assembly in a pool (in waste and EBS)	(2.1.14.09.07)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Pu accumulates in basin pool (in waste and EBS)	(2.1.14.09.08)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Accumulated 239Pu decays to 235U in basin pool (in waste and EBS)	(2.1.14.09.09)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Near-field criticality, fissile solution flows into drift low point	(2.1.14.10.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Accumulation of clays and sediments in basins (in EBS)	(2.1.14.10.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Near-field criticality, fissile solution is adsorbed or reduced in invert	(2.1.14.11.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Near-field criticality, filtered slurry or colloidal stream collects on invert surface	(2.1.14.12.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Near-field criticality associated with colloidal deposits	(2.1.14.13.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Out-of-package criticality, fuel/magma mixture	(2.1.14.14.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Critical assembly forms away from repository	(2.2.14.01.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Reconcentration (release/ migration factors)	(2.2.14.01.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Reconcentration (release/migration factors)	(2.2.14.01.02)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
DOE SNF criticality far-field (radionuclide inventory impact)	(2.2.14.01.03)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
DOE SNF criticality far-field (waste heat impact)	(2.2.14.01.04)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Far-field criticality, precipitation in organic reducing zone in or near water table	(2.2.14.02.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Precipitation of U at reducing zone associated with organics in alluvial aquifer	(2.2.14.02.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Precipitation of U at reducing zone associated w/organics in Franklin Lake playa	(2.2.14.02.02)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Far-field criticality, sorption on clay/zeolite in TSbv	(2.2.14.03.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ	(2.2.14.04.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability

Table 5. Summary of Criticality FEPs Screening Decisions (continued)

FEP Name	YMP FEP Database Number	Screening Decision	Screening Basis
Precipitation of U in the upwelling zone along some faults	(2.2.14.04.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Precipitation of U below the redox front in the SZ	(2.2.14.04.02)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Far-field criticality, precipitation in perched water above TSbv	(2.2.14.05.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Accumulation of solute in topographic lows of the altered TSbv	(2.2.14.05.01)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Far-field criticality, precipitation in fractures of TSw rock	(2.2.14.06.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Far-field criticality, dryout produces fissile salt in a perched water basin	(2.2.14.07.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability
Far-field criticality associated with colloidal deposits	(2.2.14.08.00)	*Excluded* from the TSPA–SR (Preliminary)	Low probability

8. INPUTS AND REFERENCES

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8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

10 CFR 50. Energy: Domestic Licensing of Production and Utilization Facilities. Readily Available

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.

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ATTACHMENT I

GLOSSARY

astronomical unit – (AU) A measure for distance within the solar system equal to the mean distance between earth and sun, that is, about 92,956,000 miles [149,598,000 kilometers].

asteroid – A small planet with a diameter from a fraction of a mile to nearly 500 miles.

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

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

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

comet – A celestial body that consists of a fussy head usually surrounding a bright nucleus, that often, with the part of its orbit near the sun, develops a long tail which points away from the sun and that has an orbit varying in eccentricity between nearly round and parabolic.

critical group – A theoretical group of individuals, based on observed population characteristics, which resides 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).

criticality – Criticality, as used in this document, refers to nuclear criticality, which is a self-sustaining fission chain reaction that requires a sufficient concentration and localized (critical) mass of fissionable isotopes (e.g., U-235, Pu-239). Thermal criticality requires the additional presence of neutron moderating materials (e.g., water) in a suitable geometry. Fast criticality can occur without moderator, but generally requires a much larger critical mass than thermal criticality. Criticality can be prevented by the presence of neutron absorbing elements (e.g., boron, gadolinium).

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

diagenesis – Processes involving physical and chemical changes in sediment after deposition that convert it to consolidated rock; includes compaction, cementation, recrystallization, and perhaps replacement.

diapir – A dome or anticlinal fold, the overlying rocks of which have been ruptured by squeezing out of the plastic core material. Diapirs in sedimentary strata usually contain cores of salt or shale. Igneous intrusions may also show diapiric structure.

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).

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

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

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

event – A natural or anthropogenic phenomenon that has a potential to affect disposal system performance and that occurs during an interval that is short compared to the period of performance.

Excluded FEP – A FEP that is identified by the FEP-screening process as requiring no further analysis in the quantitative TSPA, based on low probability, low consequence to dose, or on regulation.

expected FEP – An *Included* in the TSPA–SR FEP that, for the purposes of the TSPA, is assumed to occur with a probability equal to 1.0 during the period of performance.

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

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

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

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

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

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

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

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

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

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

meteor – One of the small particles of matter in the solar system observable directly only when it falls into the earth's atmosphere where friction may cause its temporary incandescence

meteorite – A meteor that reaches the surface of the earth without being completely vaporized

meteoroid – A meteor particle itself without relation to the phenomena it produces when entering the earth's atmosphere

metamorphism – Process by which consolidated rocks are altered in composition and texture, or internal structure by conditions and forces nor resulting simply from burial and weight of subsequently accumulated overburden. Pressure, heat, and the introduction of new chemical substances are the principal causes, and the resulting changes, which generally include the development of new minerals, are a thermodynamic response to a greatly altered environment. Diagenesis has been considered to be incipient metamorphism.

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.

ponding – Ponding refers to the accumulation of liquid (for example, water) or sediment in a closed topographic depression. Ponding occurs when the flux of liquid or sediment into the depression exceeds its removal by downward percolation, evaporation, or other processes. Ponding can occur at a wide range of scales, from local features on the floor of an excavated drift to regional basins. For purposes of criticality calculation, the term ponding may also apply to saturation or near saturation of groundwater in an otherwise unsaturated zone, particularly in the highly porous near-field zones (e.g., lithophysae, crushed tuff invert).

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 potentiometric surface.

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

radionuclide – radioactive type of atom with an unstable nucleus that spontaneously decays, usually emitting ionizing radiation in the process. Radioactive elements characterized by their atomic mass and number.

saltation – the process by which soil particles become temporarily suspended in the atmosphere by wind action and then bounce along the soil surface.

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

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

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.

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., overthrust belts). Also, the process by which such structures together are formed.

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

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

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

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

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

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

volcano – A geologic feature than includes an edifice of magmatic material erupted on the land surface, one or more conduits that feed the eruption, and a dike or dike system that 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 partially melted together (welded) during compaction of the ash bed while the ash was still hot.

ATTACHMENT II

SYSTEM-LEVEL FEPS: PRIMARY AND SECONDARY FEP DESCRIPTIONS

Primary: Timescales of Concern

FEP Number (0.1.02.00.00)	**Primary Description:** This FEP describes the timescale of concern over which the disposal system presents a significant health or environmental hazard.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included in TSPA–SR*	**Screening Decision Basis**: Does not satisfy a screening criterion
Number of Secondaries: 0	

Primary: Spatial Domain of Concern

FEP Number (0.1.03.00.00)	**Primary Description:** This FEP describes the spatial domain of concern over which the disposal system *[may]* present a significant health or environmental hazard.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included in the TSPA–SR*	**Screening Decision Basis**: Does not satisfy a screening criterion
Number of Secondaries: 0	

Primary: Regulatory Requirements and Exclusions

FEP Number (0.1.09.00.00)	**Primary Description:** This FEP describes regulatory requirements and guidance specific to the proposed Yucca Mountain repository.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included in the TSPA–SR*	**Screening Decision Basis**: Does not satisfy a screening criterion
Number of Secondaries: 2	

Primary: **Regulatory Requirements and Exclusions**
Secondary: Assessment Basis FEP

FEP Number (0.1.09.00.01)	**Originator FEP Description**: FEPs relating to the assessment basis are not included in the WIPP CCA FEP list. The CCA has been compiled to show compliance with 40 CFR Part 191 and 40 CFR Part 194. These regulations specify, inter alia, the timescale of concern and assumptions regarding future human behavior. (WIPP)

Primary: **Regulatory Requirements and Exclusions**
Secondary: Assessment Basis FEP (atmospheric processes)

FEP Number (0.1.09.00.02)	**Originator FEP Description**: FEPs relating to atmospheric transport are not included in the WIPP CCA FEP list. The CCA has been compiled to show compliance with 40 CFR Part 191 and 40 CFR Part 194. These regulations specify release limits to the accessible environment. (WIPP)

Primary: Model and Data Issues

FEP Number (0.1.10.00.00)	**Primary Description:** This FEP describes issues identified by other programs related to modeling of the disposal system. Model and data issues are general (i.e., methodological) issues affecting the assessment modeling process and use of data. These issues include the approach and assumptions associated with the selection of conceptual models, the mathematical implementation of conceptual models, model geometry and dimensionality, models of coupled processes, and boundary and initial conditions. These issues also include the derivation of data values and correlations.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included in the TSPA–SR*	**Screening Decision Basis**: Does not satisfy a screening criterion
Number of Secondaries: 11	

Primary: **Model and Data Issues**
Secondary: Boundary Conditions

FEP Number (0.1.10.00.01)	**Originator FEP Description**: Processes occurring at the boundaries or interfaces between the waste matrices, container, buffer, backfill and rock may be important. (AECL)

Primary: **Model and Data Issues**
Secondary: Uncertainties (repository)

FEP Number (0.1.10.00.02)	**Originator FEP Description**: The vault system consists of many important components that could have complex physical and chemical interactions. Considerable uncertainties will exist in modeling its behavior over 10,000 yrs. "...The effects of these uncertainties should be included in assessments..." (AECL)

Primary: **Model and Data Issues**
Secondary: Correlation

FEP Number (0.1.10.00.03)	**Originator FEP Description**: Some parameters used to define the geosphere model should be correlated to one another. For example, parameters that describe the behavior of similar chemical elements are often similar, such as solubilities of Uranium and Thorium, etc. (AECL)

Primary: **Model and Data Issues**
Secondary: Uncertainties (geosphere)

FEP Number (0.1.10.00.04)	**Originator FEP Description**: The geosphere system is very difficult to model because it is difficult to access. ... Considerable uncertainties will exist in describing its current behavior, and extrapolating this behavior for thousands of years into the future. etc. (AECL).

Primary: **Model and Data Issues**
Secondary: Correlation

FEP Number (0.1.10.00.05)	**Originator FEP Description**: Model parameters are not always independent; that is, given a value for one parameter, the value for another may be restrained or fixed. For example, the amount of food a person consumes is related to the amount of water consumed, and the degree of root uptake of a contaminant is related to the solubility of the contaminant in the soil. (AECL)

Primary: **Model and Data Issues**
Secondary: Uncertainties (biosphere)

FEP Number (0.1.10.00.06)	**Originator FEP Description**:. The biosphere is complex and it involves a wide variety of interacting physical, chemical and biological factors. The biosphere is constantly changing over time in an often unpredictable way and this raises additional uncertainties. etc. (AECL)

Primary: **Model and Data Issues**
Secondary: Model and data issues

FEP Number (0.1.10.00.07)	**Originator FEP Description**: The WIPP CCA does not treat model and data issues as features, events or processes (FEPs). These issues are discussed in the CCA in Chapter 6 (which describes the overall modeling approach), Appendix MASS (which highlights the modeling assumptions made in the CCA), Appendix PAR (which presents data values and their derivations), and supporting Appendices which describe the implementation of PA models. (WIPP)

Primary: **Model and Data Issues**
Secondary: Unmodeled design features

FEP Number (0.1.10.00.08)	**Originator FEP Description**: Some design features of the vault may be important and might require explicit modeling. For example, there may be significant differences between the designed version and the constructed version; a need for retrievability may lead to unforeseen modifications, etc. (AECL)

Primary: **Model and Data Issues**
Secondary: Disposal geometry

FEP Number (0.1.10.00.09)	**Originator FEP Description**: The performance assessment represents the three dimensional geometry of the disposal system (repository, shafts, and controlled area) using two primary two-dimensional simplifications. The BRAGFLO (BRine And Gas FLOw) computer code uses a geometry that approximates a north-south vertical cross-section through the disposal system and some of the surrounding rock. Effects of flow in the third (out-of-plane) dimension are approximated with a two dimensional element configuration that simulates convergent or divergent flow to the north and south, centered on the repository, in intact rocks laterally away from the repository. (WIPP)

Primary: **Model and Data Issues**
Secondary: Conceptual model hydrology

FEP Number (0.1.10.00.10)	**Originator FEP Description**: The conceptual model of the geosphere may be incorrect, due to invalid assumptions about porous versus fracture flow, and the presence or absence of fractures. Other conceptual models might be equally likely. (AECL)

Primary: **Model and Data Issues**
Secondary: Correlation (contaminant speciation and solubility)

FEP Number (0.1.10.00.11)	**Originator FEP Description**: Model parameters are not always independent; that is given a value for one parameter, the value for another may be constrained or fixed. (AECL)

Primary: Records and Markers, Repository

FEP Number (1.1.05.00.00)	**Primary Description:** This category contains FEPs related to the retention of records of the contents of the repository and markers constructed to inform future humans of the location and contents of the repository. Performance assessments must consider the potential effects of human activities that might take place within the controlled area at a future time when institutional controls and/or knowledge of the presence of a repository cannot be assumed.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included* for construction of markers to inform future humans of the location and contents of the repository, retention of records, and for lack of knowledge of the repository at future times / *Excluded* from the TSPA–SR for efficacy of markers and record retention to prevent intrusion after 100-years postclosure period.	**Screening Decisions Basis:** Does not satisfy a screening criterion / By Regulation
Number of Secondaries: 4	

Primary: **Records and Markers, Repository**
Secondary: Loss of Records

FEP Number (1.1.05.00.01)	**Originator FEP Description**: "Knowledge of the final repository could conceivably have been lost at some point in time in the future, either as a result of some catastrophic event such as a global war of extermination" (FEP J6.07) "or as a consequence of human life being rendered impossible due to a new glaciation" (FEP J5.42) "If the country is thereafter repopulated, it is conceivable that certain activities might violate the barriers of the final repository". (Joint SKI/SKB)

Primary: **Records and Markers, Repository**
Secondary: Repository records, markers

FEP Number (1.1.05.00.02)	**Originator FEP Description**: Records of a repository location will be lodged in local and national libraries and archives. Repository markers have been considered especially in the USA (e.g., Human Interference Task Force 1984) but are of uncertain efficacy. etc. (NAGRA)

Primary: **Records and Markers, Repository**
Secondary: Loss of Records

FEP Number (1.1.05.00.03)	**Originator FEP Description**: (none)(NEA)

Primary: **Records and Markers, Repository**
Secondary: Loss of Records

FEP Number (1.1.05.00.04)	**Originator FEP Description**: Human activities will be prevented from occurring within the controlled area in the near future. However, performance assessments must consider the potential effects of human activities that might take place within the controlled area at a time when institutional controls cannot be assumed to eliminate completely the possibility of human intrusions. (WIPP)

Primary: Repository Design

FEP Number (1.1.07.00.00)	**Primary Description:** This category contains FEPs related to the design of the repository, and the ways in which the design contributes to long-term performance. Changes to or deviations from the specified design may affect the long-term performance of the disposal system.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included* for licensed repository design and for design modifications / *Excluded* for significant undetected deviations from design / *Excluded* for inadequacy or lack of safety of the proposed design and for non-YMP design elements	**Screening Decision Basis**: Does not satisfy a screening criterion / Low consequence to dose / By regulation
Number of Secondaries: 8	

Primary: **Repository Design**
Secondary: Poorly-designed repository

FEP Number (1.1.07.00.01)	**Originator FEP Description**: The repository design is inadequate to meet the regulatory criteria or meets the criteria but is demonstrably unsafe. (Joint SKI/SKB)

Primary: **Repository Design**
Secondary: Design modification

FEP Number (1.1.07.00.02)	**Originator FEP Description**: (none) (NEA)

Primary: **Repository Design**
Secondary: HLW panels (siting)

FEP Number (1.1.07.00.03)	**Originator FEP Description**: The HLW panels, each consist of an array of parallel horizontal disposal tunnels. These will be sited to "fit" into undisturbed crystalline blocks with a minimum distance of 100 m to the nearest 1st or 2nd order fault or other disturbed zone. etc. (NAGRA)

Primary: **Repository Design**
Secondary: TRU silos (siting)

FEP Number (1.1.07.00.04)	**Originator FEP Description**: The TRU (long-lived intermediate-level or "transuranic" waste) silos contain large quantities of cementitious backfill and structural material, as well as small quantities of organic material within disposed wastes. Over time, the interactions of groundwater with the silos will lead to a plume of cementitious species, which is expected to alter the mineralogy of water-conducting features in its path. (NAGRA)

Primary: **Repository Design**
Secondary: Access tunnels and shafts

FEP Number (1.1.07.00.05)	**Originator FEP Description**: Access tunnels and shafts will connect the various repository elements and may cross higher -permeability rock zones (i.e., MWCFs) in the crystalline basement. The orientation of the access tunnels may be arranged so that access to a given block is only from one direction, thus minimizing the likelihood of significant flow along access tunnels. (NAGRA)

Primary: **Repository Design**
Secondary: Design and construction FEPs

FEP Number (1.1.07.00.06)	**Originator FEP Description**: FEPs relating to different designs, and to constructional, operational and decommissioning errors are not included in the WIPP CCA FEP list. The CCA is an application for disposal based on a specific design of the repository and seals. Operating procedures for waste emplacement are also specified. (WIPP)

Primary: **Repository Design**
Secondary: Design and construction

FEP Number (1.1.07.00.07)	**Originator FEP Description**: (none) (NEA)

Primary: **Repository Design**
Secondary: Design and construction FEPs

FEP Number (1.1.07.00.08)	**Originator FEP Description**: FEPs relating to different designs, and to constructional, operational and decommissioning errors are not included in the WIPP CCA FEP list. The CCA is an application for disposal based on a specific design of the repository and seals. Operating procedures for waste emplacement are also specified. etc. (WIPP)

Primary: Quality Control

FEP Number (1.1.08.00.00)	**Primary Description:** This category contains FEPs related to quality assurance and control procedures and tests during the design, construction, and operation of the repository, as well as the manufacture of the waste forms, containers, and engineered features. Lack of quality control could result in material defects, faulty waste package fabrication, and faulty or non-design-standard construction, all of which may lead to reduced effectiveness of the engineered barriers.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included* in the TSPA–SR for Primary FEP and for Secondary FEPs (1.1.08.00.05) and (1.1.08.00.06) / *Excluded* from the TSPA–SR for Secondary FEPs addressing material defects, faulty fabrication and faulty or non-design-standard construction) / *Excluded* from the TSPA–SR for Secondary FEPs addressing the installation of panel, silos, and drains)	**Screening Basis:** Does not satisfy a screening criterion / Low consequence to dose/ By Regulation
Number of Secondaries: 7	

Primary: **Quality Control**
Secondary: Poorly constructed repository

FEP Number (1.1.08.00.01)	**Originator FEP Description**: A poor execution of (a good design of) a repository may cause enhanced degradation of the engineered barriers and unwanted alterations in the nearby rock. (Joint SKI/SKB)

Primary: **Quality Control**
Secondary: Material Defects

FEP Number (1.1.08.00.02)	**Originator FEP Description**: (none) (NEA)

Primary: **Quality Control**
Secondary: Common cause failures

FEP Number (1.1.08.00.03)	**Originator FEP Description**: (none) (NEA)

Primary: **Quality Control**
Secondary: Poor quality construction

FEP Number (1.1.08.00.04)	**Originator FEP Description**: none) (NEA)

Primary: **Quality Control**
Secondary: Quality Control

FEP Number (1.1.08.00.05)	**Originator FEP Description**: Strict quality control is applied during the manufacture of the glass resulting in a homogeneous and well characterized product. etc. (NAGRA)

Primary: **Quality Control**
Secondary: Quality Control

FEP Number (1.1.08.00.06)	**Originator FEP Description**: Quality control will be exercised on canister manufacture and sealing. Fabrication quality is ensured through, for example, a simple sand-mold casting production method and ultrasonic inspection of the completed canister, lid and weld, (NAGRA)

Primary: **Quality Control**
Secondary: Drains, installed to divert water around containers, are improperly placed.

FEP Number (1.1.08.00.07)	**Originator FEP Description**: Drains, installed to divert water around containers, are improperly placed or omitted altogether over some canisters. (YMP)

Primary: Schedule and Planning

FEP Number (1.1.09.00.00)	**Primary Description:** This category contains FEPs related to the sequences of events and activities occurring during construction, operation, and closure of the repository. Deviations from the design construction or waste emplacement schedule may affect the long-term performance of the disposal system.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis**: By Regulation
Number of Secondaries: 1	

Primary: **Schedule and Planning**
Secondary: Effects of phased operation

FEP Number (1.1.09.00.01)	**Originator FEP Description**: (none) (NEA)

Primary: Administrative Control, Repository Site

FEP Number (1.1.10.00.00)	**Primary Description:** This category contains FEPs related to administrative control of the repository site. Administrative control can reduce the possibility that human activities might take place within the controlled area.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included* in the TSPA–SR for administrative control during preclosure period, for initial construction of markers and archiving of records, and for subsequent loss of administrative control and for Secondary FEPs / *Excluded* from the TSPA–SR for efficacy of administrative controls beyond 100 years of the postclosure period.	**Screening Decision Basis**: Does not satisfy a screening criterion / By Regulation- (a human-intrusion scenario must be considered regardless of the status of administrative control.)
Number of Secondaries: 1	

Primary: **Administrative Control, Repository Site**
Secondary: Planning Restrictions

FEP Number (1.1.10.00.01)	**Originator FEP Description**: It is expected that human intrusion into a repository would be prevented (or possibly reduced) by planning restrictions. However, HSK/KSA Protection Objective 3 requires that long-term repository safety must not rely on administrative measures. Therefore, such planning restrictions are neglected in long-term safety assessment. (NAGRA)

Primary: Monitoring of Repository

FEP Number (1.1.11.00.00)	**Primary Description:** This category contains FEPs related to monitoring that is carried out during or after operations, for either operational safety or verification of long-term performance. Monitoring boreholes could provide enhanced pathways between the surface and the repository.	
Primary Assigned to: *System-Level FEPs*		
Screening Decision: *Excluded* from the TSPA–SR for Primary and Secondary FEPs with the exception of the Secondary FEP "Monitoring and remedial activities (1.1.11.00.0 / *Included* in the TSPA–SR for monitoring wells and boreholes as addressed by the human-intrusion scenario and for Secondary FEP "Monitoring and remedial activities" (1.1.11.00.01).	**Screening Decision Basis**: Low consequence to dose / Does not satisfy a screening criterion	
Number of Secondaries: 4		

Primary: **Monitoring of Repository**
Secondary: Monitoring and remedial activities

FEP Number (1.1.11.00.01)	**Originator FEP Description**: Boreholes used to monitor performance could provide pathways for contaminant transport. Similarly, some activities to remedy problems could lead to enhanced transport. (AECL)

Primary: **Monitoring of Repository**
Secondary: Postclosure monitoring

FEP Number (1.1.11.00.02)	**Originator FEP Description**: Postclosure monitoring schemes must be designed with care. A monitoring well represents a short path to the biosphere and may also be used for a water supply. etc. (Joint SKI/SKB)

Primary: **Monitoring of Repository**
Secondary: Post-closure monitoring

FEP Number (1.1.11.00.03)	**Originator FEP Description**: (none) (NEA)

Primary: **Monitoring of Repository**
Secondary: Postclosure monitoring

FEP Number (1.1.11.00.04)	**Originator FEP Description**: Monitoring methods may be detrimental to the performance of the disposal system. Postclosure monitoring is required by 40 CFR 191.14(b) as an assurance requirement to "detect substantial and detrimental deviations from performance". etc. (WIPP)

Primary: Accidents and Unplanned Events During Operation

FEP Number (1.1.12.01.00)	**Primary Description:** The long-term performance of the disposal system might be seriously affected by unplanned or improper activities that take place during construction, operation, and closure of the repository.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded from the TSPA–SR*	**Screening Decision Basis**: Low consequence to dose for Primary and Secondary FEPs, By Regulation for "Sabatoge and improper operation" (1.1.12.01.02).
Number of Secondaries: *6*	

Primary: **Accidents and Unplanned Events During Operation**
Secondary: Preclosure events

FEP Number (1.1.12.01.01)	**Originator FEP Description**: Unplanned events occurring during the preclosure phase could have serious consequences on the postclosure phase; for example, flooding of the vault could alter local groundwater characteristics, unwanted organic materials could be introduced, etc. (AECL

Primary: **Accidents and Unplanned Events During Operation**
Secondary: Sabotage and improper operation

FEP Number (1.1.12.01.02)	**Originator FEP Description**: Sabotage and/or improper operation could compromise the long-term performance of the vault. Examples include, sabotage of vault containers, seals, backfill and buffer; undesirable or unexpected material left in the vault: explosions changing vault integrity, etc. (AECL)

Primary: **Accidents and Unplanned Events During Operation**
Secondary: Accidents during operation

FEP Number (1.1.12.01.03)	**Originator FEP Description**: ... The most severe consequence of an accident during the operational phase would be if the accident leads to an inability to close the repository. The probability for such an event is judged to be extremely low. (Joint SKI/SKB)

Primary: **Accidents and Unplanned Events During Operation**
Secondary: Accidents during operation

FEP Number (1.1.12.01.04)	**Originator FEP Description**: ... (none) (NEA)

Primary: **Accidents and Unplanned Events During Operation**
Secondary: Handling accidents

FEP Number (1.1.12.01.05)	**Originator FEP Description**: Handling accidents, e.g., dropped canister, could result in damage to the stainless steel fabrication flask and /or additional cracking of the glass. etc. (NAGRA)

Primary: **Accidents and Unplanned Events During Operation**
Secondary: Oil or organic fluid spill

FEP Number	**Originator FEP Description**: Some spillages of oil, hydraulic fluid or organic solvents are likely to occur during repository construction and operation. The nature of equipment and fluids in use in the repository would be controlled and strict maintenance procedures followed to minimize the possibilities of such spills. etc. (NAGRA)
(1.1.12.01.06)	

Primary: Retrievability

FEP Number (1.1.13.00.00)	**Primary Description:** This category contains FEPs related to design, emplacement, operational, or administrative measures that might be applied or considered in order to enable or ease retrieval of wastes. There may be a requirement to retrieve all or part of the waste stored in the repository; for example, to recover valuable fissile materials or to replace defective containers.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included* in the TSPA–SR for Primary and Secondary FEPs related to design elements and emplacement/ *Excluded* from the TSPA–SR for operational and administrative considerations.	Screening Decision Basis: Does not satisfy a screening criterion / By Regulation
Number of Secondaries: 1	

Primary: **Retrievability**
Secondary: Retrieveability

FEP Number	**Originator FEP Description**: There may be a requirement to retrieve all or part of the waste stored in the vault; for example, to recover valuable fissile materials or to replace defective containers. (AECL)
(1.1.13.00.01)	

Primary: Metamorphism

FEP Number (1.2.05.00.00)	**Primary Description:** This category of includes FEPs related to regional metamorphism, which has the potential to affect the long-term performance of the repository if it occurs. Metamorphic activity is defined as solid state recrystallization changes to rock properties and geologic structures through the effects of heat and/or pressure.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded from the TSPA–SR*	**Screening Decision Basis:** Low consequence to dose
Number of Secondaries: 4	

Primary: **Metamorphism**
Secondary: Metamorphic activity

FEP Number	**Originator FEP Description:** (none) (NEA)
(1.2.05.00.01)	

Primary: **Metamorphism**
Secondary: Regional metamorphism

FEP Number	**Originator FEP Description:** The onset of regional metamorphism as a consequence of the deep burial of northwest England. Such an event would radically change the properties of the host rock and would effectively erase the repository. etc. (UK-HMIP)
(1.2.05.00.02)	

Primary: **Metamorphism**
Secondary: Metamorphic activity

FEP Number	**Originator FEP Description:** Metamorphic activity is defined as solid state recrystallization changes to rock properties and geologic structures through the effects of heat and/or pressure, Metamorphic activity requires depths of burial much greater than the depth of the repository. etc. (WIPP)
(1.2.05.00.03)	

Primary: **Metamorphism**
Secondary: Metamorphic activity

FEP Number	**Originator FEP Description:** Metamorphic activity could cause activation, creation, or sealing of faults; changes in topography; changes in rock stress; deformation of rock; changes in groundwater temperatures. (AECL)
(1.2.05.00.04)	

Primary: Diagenesis

FEP Number (1.2.08.00.00)	**Primary Description:** This category contains FEPs related to natural processes that alter the mineralogy, or other properties, of rocks after the rocks have formed, under temperature and pressure conditions normal to the upper few kilometers of the earth's crust. Diagenesis includes chemical, physical and biological processes that take place in rocks after formation but before eventual metamorphism or weathering.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis:** Low consequence to dose
Number of Secondaries: 4	

Primary: **Diagenesis**
Secondary: Diagenesis

FEP Number (1.2.08.00.01)	**Originator FEP Description:** Chemical, physical and biological processes that takes place in sediments or sedimentary rock after formation but before eventual metamorphism or weathering. (Joint SKI/SKB)

Primary: **Diagenesis**
Secondary: Diagenesis

FEP Number (1.2.08.00.02)	**Originator FEP Description:** The physiochemical alteration of a sediment during compaction and cementation as a consequence of shallow burial. (UK-HMIP)

Primary: **Diagenesis**
Secondary: Fracture infills

FEP Number (1.2.08.00.03)	**Originator FEP Description:** Precipitation of minerals as fracture infills can reduce hydraulic conductivities. (WIPP)

Primary: **Diagenesis**
Secondary: Diagenesis

FEP Number (1.2.08.00.04)	**Originator FEP Description:** (none) (NEA)

Primary: Salt Diapirism and Dissolution

FEP Number (1.2.09.00.00)	**Primary Description:** This category contains FEPs related to System-Level Processes primarily relevant to repositories located in salt. Diapirism refers to the tendency of any rock, but most particularly salt, to flow under lithostatic loading when density and viscosity contrasts with surrounding strata are favorable. Salt domes are the best-known example of salt diapirism. Dissolution can occur when any soluble mineral is removed by flowing water, and large-scale dissolution is a potentially important process in rocks that are composed predominantly of water-soluble evaporite minerals, such as salt.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis:** By Regulation and Low consequence to dose
Number of Secondaries: 0	

Primary: Diapirism

FEP Number (1.2.09.01.00)	**Primary Description:** The process by which plastic, low density rocks (most commonly evaporites) may flow under lithostatic loading when density and viscosity contrasts with surrounding strata are favorable. Such a process would modify the groundwater flow regime and affect radionuclide transport.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis:** By Regulation (for salt diapirism) and Low consequence to dose (for igneous diapirism).
Number of Secondaries: 3	

Primary: **Diapirism**
Secondary: Diapirism

FEP Number (1.2.09.01.01)	**Originator FEP Description:** (none) (NEA)

Primary: **Diapirism**
Secondary: Salt deformation

FEP Number (1.2.09.01.02)	**Originator FEP Description:** Deformed salt in the lower Salado and upper strata of the Castile has been encountered in a number of boreholes around WIPP. (WIPP)

Primary: **Diapirism**
Secondary: Diapirism

FEP Number (1.2.09.01.03)	**Originator FEP Description:** Deformed salt in the lower Salado and upper strata of the Castile has been encountered in a number of boreholes around WIPP. A number of mechanisms may result in salt deformation, including gravity foundering, dissolution, gravity sliding, gypsum dehydration, and depositional processes. etc. (WIPP)

Primary: Deliberate Human Intrusion

FEP Number (1.4.02.01.00)	**Primary Description:** Humans could deliberately intrude into the repository. Without appropriate precautions, intruders could experience high radiation exposures. Moreover, containment may be left damaged, which could increase radionuclide release rates to the biosphere. Motivation for deliberate human intrusion includes mining, waste retrieval, site remediation/improvement, archaeology, sabotage, and acts of war.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR for Deliberate Intrusion / *Included* in the TSPA–SR a stylized human-intrusion scenario.	**Screening Decision Basis:** By Regulation / Does not satisfy a screening criterion
Number of Secondaries: 18	

Primary: **Deliberate Human Intrusion**
Secondary: Chemical sabotage

FEP Number (1.4.02.01.01)	**Originator FEP Description:** Intentional sabotage actions to impair the barrier functions of the repository may be planned (and planted) during the operation stage. Internal security actions must be taken to prevent this type of sabotage. (Joint SKI/SKB)

Primary: **Deliberate Human Intrusion**
Secondary: Waste retrieval, mining

FEP Number (1.4.02.01.02)	**Originator FEP Description**: The repository is mined to recover resources. (Joint SKI/SKB)

Primary: **Deliberate Human Intrusion**
Secondary: Archeological intrusion

FEP Number (1.4.02.01.03)	**Originator FEP Description**: Archeological intrusion can not be ruled out especially after loss of records (or lost real understanding of records). Warning messages would probably only encourage an ambitious researcher! (Joint SKI/SKB)

Primary: **Deliberate Human Intrusion**
Secondary: Recovery of repository materials

FEP Number (1.4.02.01.04)	**Originator FEP Description**: (none) (NEA)

Primary: **Deliberate Human Intrusion**
Secondary: Malicious intrusion

FEP Number (1.4.02.01.05)	**Originator FEP Description**: (none) (NEA)

Primary: **Deliberate Human Intrusion**
Secondary: Archaeological investigation

FEP Number (1.4.02.01.06)	**Originator FEP Description**: (none) (NEA)

Primary: **Deliberate Human Intrusion**
Secondary: Deliberate intrusion

FEP Number (1.4.02.01.07)	**Originator FEP Description**: Purposeful drilling or tunneling into the repository with the full knowledge of its nature and subsequent consequences. (UK-HMIP).

Primary: **Deliberate Human Intrusion**
Secondary: Malicious intrusion

FEP Number (1.4.02.01.08)	**Originator FEP Description**: Purposeful drilling or tunneling into the repository with the intent of releasing harmful radionuclides to the surface. (UK-HMIP)

Primary: **Deliberate Human Intrusion**
Secondary: Deliberate drilling intrusion

FEP Number (1.4.02.01.09)	**Originator FEP Description**: Consistent with 40 CFR 194.33(b) (1), all near-future and future human-initiated FEPs relating to deliberate intrusion into the WIPP excavation have been eliminated from performance assessment calculations on regulatory grounds. (WIPP)

Primary: **Deliberate Human Intrusion**
Secondary: Archeological investigations

FEP Number (1.4.02.01.10)	**Originator FEP Description**: ... Archeological investigations in the WIPP area have involved only minor surface disturbances and have not involved drilling. Consistent with the future states assumptions in 40 CFR 194.25(a), such drilling activities have been eliminated from performance assessment calculations on regulatory grounds. (WIPP)

Primary: **Deliberate Human Intrusion**
Secondary: Post-closure surface activities (intrusion)

FEP Number (1.4.02.01.11)	**Originator FEP Description**: (none) (NEA)

Primary: **Deliberate Human Intrusion**
Secondary: Intrusion into accumulation zone in biosphere

FEP Number (1.4.02.01.12)	**Originator FEP Description**: This is only related to the BIOSPHERE. (Joint SKI/SKB)

Primary: **Deliberate Human Intrusion**
Secondary: Unsuccessful attempt at site improvement

FEP Number (1.4.02.01.13)	**Originator FEP Description**: An effort intended for improving the site and/or the technical barriers (also post closure) may in fact worsen the situation. (Joint SKI/SKB)

Primary: **Deliberate Human Intrusion**
Secondary: Sabotage

FEP Number (1.4.02.01.14)	**Originator FEP Description**: Acts of sabotage, during or after closure, may affect flow properties. (AECL)

Primary: **Deliberate Human Intrusion**
Secondary: Sabotage

FEP Number (1.4.02.01.15)	**Originator FEP Description**: (none) (NEA)

Primary: **Deliberate Human Intrusion**
Secondary: Sudden energy release (in waste and EBS)

FEP Number (1.4.02.01.16)	**Originator FEP Description**: Sudden energy release could occur by sabotage during the operational period. (Joint SKI/SKB)

Primary: **Deliberate Human Intrusion**
Secondary: Other future uses of crystalline rock

FEP Number (1.4.02.01.17)	**Originator FEP Description**: Granite may certainly be a useful raw material in the future. [There follows an argument for rejecting this FEP]. (Joint SKI/SKB)

Primary: **Deliberate Human Intrusion**
Secondary: Intrusion (human)

FEP Number (1.4.02.01.18)	**Originator FEP Description**: Human intrusion could occur during the post-closure phase for a number of reasons, such as recovery of resources. (AECL)

Primary: Inadvertent Human Intrusion

FEP Number (1.4.02.02.00)	**Primary Description:** Humans could accidentally intrude into the repository. Without appropriate precautions, intruders could experience high radiation exposures. Moreover, containment may be left damaged, which could increase radionuclide release rates to the biosphere. Inadvertent human intrusion might occur during scientific, mineral or geothermal exploration.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included in the TSPA–SR*	**Screening Decision Basis**: Does not satisfy a screening criterion
Number of Secondaries: 1	

Primary: **Inadvertent Human Intrusion**
Secondary: Accidental intrusion

FEP Number (1.4.02.02.01)	**Originator FEP Description**: Drilling, tunneling or mining into the repository without knowledge of its existence. While obviously undesirable, it is conceivable that at some time in the future the repository may be drilled, tunneled or mined into by accident, or without knowledge of the consequences. There are countless possible reasons why this may occur, e.g., exploratory drilling, exploitation drilling, archaeological excavations, injection of liquid wastes etc. Despite the large number of possible accidental intrusion scenarios, the range of outcomes of all of them is thought to be quite similar. [A discussion of three summary modes of intrusion follows] (UK-HMIP)

Primary: Unintrusive Site Investigation

FEP Number (1.4.03.00.00)	**Primary Description:** This category contains FEPs related to airborne, geophysical, or other surface-based investigations of a repository site after its closure.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded from the TSPA–SR*	**Screening Decision Basis**: Low consequence to dose
Number of Secondaries: 0	

Primary: Drilling Activities (Human Intrusion)

FEP Number (1.4.04.00.00)	**Primary Description:** This category contains FEPs related to any type of drilling activity in the repository environment. These may be taken with or without knowledge of the repository. Drilling activities may be associated with natural resource exploration (water, oil and gas, minerals, geothermal energy), waste disposal (liquid), fluid storage (hydrocarbon, gas), or reopening existing boreholes.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included* in the TSPA–SR for a stylized drilling scenario / *Excluded* from the TSPA–SR for specific types of drilling scenarios	**Screening Decision Basis**: Does not satisfy a screening criterion / By Regulation
Number of Secondaries: 27	

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Geothermal

FEP Number (1.4.04.00.01)	**Originator FEP Descriptions**: Geothermal energy is not considered to be a potentially exploitable resource because economically attractive geothermal conditions do not exist in the northern Delaware Basin. No drilling associated with geothermal energy production has taken place in the Delaware Basin. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Other resources

FEP Number (1.4.04.00.02)	**Originator FEP Description**: Drilling to explore other resources has taken place and is expected to continue in the Delaware Basin. The potential effects of existing and possible near-future boreholes on fluid flow and radionuclide transport within the disposal system are discussed in FEPs W3.021 through W3.026, and eliminated based on low consequence. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Enhanced oil and gas recovery

FEP Number (1.4.04.00.03)	**Originator FEP Description**: ... Secondary and tertiary oil and gas production techniques can involve drilling of additional wells for the injection of fluid to enhance recovery. As indicated by the NMBMMR (1995), secondary production (water flooding) is employed in the Delaware Basin, the nearest location being approximately 2 miles from the outer boundary of the controlled area. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Liquid waste disposal

FEP Number (1.4.04.00.04)	**Originator FEP Description**: ... Consistent with 40 CFR 194.25(a), drilling for purposes other than resource recovery (such as WIPP site investigation), and drilling activities that have not taken place in the Delaware Basin over the last 100 years, need not be considered in determining future drilling rates. Thus, drilling associated with liquid waste disposal has been eliminated from performance assessment calculations. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Hydrocarbon storage

FEP Number (1.4.04.00.05)	**Originator FEP Description**: ... Consistent with 40 CFR 194.25(a), drilling for purposes other than resource recovery (such as WIPP site investigation), and drilling activities that have not taken place in the Delaware Basin over the last 100 years, need not be considered in determining future drilling rates. Thus, drilling associated with hydrocarbon storage disposal has been eliminated from performance assessment calculations. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Exploratory drilling for hydrocarbons

FEP Number (1.4.04.00.06)	**Originator FEP Description**: Hydrocarbons, produced from sedimentary structures below the tuffs are trapped in the tuffs as in Railroad Valley. (YMP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Exploratory drilling for metals

FEP Number (1.4.04.00.07)	**Originator FEP Description**: Exploratory drilling for metals occurs in and around Yucca Mtn. with possible penetration of the workings (YMP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Boreholes – exploration

FEP Number (1.4.04.00.08)	**Originator FEP Description**: Exploratory boreholes could intersect the contaminant plume or the vault, affecting flow regimes and/or transport pathways. (AECL)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Injection of liquid waste

FEP Number (1.4.04.00.09)	**Originator FEP Description**: (none) (NEA)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Exploratory drilling

FEP Number (1.4.04.00.10)	**Originator FEP Description**: (none) (NEA)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Exploitation drilling

FEP Number	Originator FEP Description
(1.4.04.00.11)	**Originator FEP Description**: (none) (NEA)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Exploratory drilling

FEP Number	Originator FEP Description
(1.4.04.00.12)	**Originator FEP Description**: Exploratory boreholes may be sunk in the repository region in search of natural resources, e.g., minerals, oil, gas, or to identify geothermal sources or geological formations suitable for disposal of liquid wastes by injection. etc. (NAGRA)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Geothermal exploitation

FEP Number	Originator FEP Description
(1.4.04.00.13)	**Originator FEP Description**: The potential for extraction of geothermal energy in Northern Switzerland has been discussed in RYBACH (1992a) and RYBACH (1992b). Two categories are considered: a) natural resources(thermal spring and stratiform aquifers), b) resources for artificially aided heat extraction (vertical heat exchanger and Hot Dry Rock systems) [A detailed discussion of resources follows] (NAGRA)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Liquid waste injection

FEP Number	Originator FEP Description
(1.4.04.00.14)	**Originator FEP Description**: Technologies exist for the disposal of liquid waste deep underground in suitable geologic formations by injection. etc. (NAGRA)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Oil and gas exploration

FEP Number	Originator FEP Description
(1.4.04.00.15)	**Originator FEP Description**: ... Drilling associated with oil and gas exploration and oil and gas exploitation currently takes place in the vicinity of the WIPP. For example, gas is extracted from reservoirs in the Morrow Formation, some 14,000 feet below the surface, and oil is extracted from shallower units within the Delaware Mountain Group, some 7,000 to 8,000 feet below the surface. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Potash exploration

FEP Number	Originator FEP Description
(1.4.04.00.16)	**Originator FEP Description**: ... The WIPP location has been evaluated for the occurrence of natural resources in economic quantities. ... Powers et al. (1978) investigated the potential for exploitation of potash, hydrocarbons, gypsum, salt, uranium, sulfur, and lithium. etc. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Water resource exploration

FEP Number	Originator FEP Description
(1.4.04.00.17)	**Originator FEP Description**: Shallow drilling associated with water, potash, sulfur, oil, and gas extraction has taken place in the Delaware Basin over the past 100 years. etc. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Oil and gas exploration

FEP Number (1.4.04.00.18)	**Originator FEP Description**: ... Drilling associated with oil and gas exploration and oil and gas exploitation currently takes place in the vicinity of the WIPP. For example, gas is extracted from reservoirs in the Morrow Formation, some 14,000 feet below the surface, and oil is extracted from shallower units within the Delaware Mountain Group, some 7,000 to 8,000 feet below the surface. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Groundwater exploitation

FEP Number (1.4.04.00.19)	**Originator FEP Description**: Shallow drilling associated with water, potash, sulfur, oil, and gas extraction has taken place in the Delaware Basin over the past 100 years. etc. (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Geothermal energy production

FEP Number (1.4.04.00.20)	**Originator FEP Description**: Geothermal production is an intrusion problem similar to the well (J5.41), active pumping will affect flow paths severely. etc. (Joint SKI/SKB).

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Geothermal energy production

FEP Number (1.4.04.00.21)	**Originator FEP Description**: (none) (NEA)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Borehole – well

FEP Number (1.4.04.00.22)	**Originator FEP Description**: A borehole could be reopened and used as a well (AECL)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Reuse of boreholes

FEP Number (1.4.04.00.23)	**Originator FEP Description**: The boreholes (drilled in the pre investigation or construction phases or for postclosure monitoring (see J5.39) are probably cheaper and less complicated to reopen than to drill new holes. (Joint SKI/SKB)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Oil and Gas extraction

FEP Number (1.4.04.00.24)	**Originator FEP Description**: ... The removal of confined fluid from oil- and gas-bearing units can cause compaction in some geologic settings, potentially resulting in subvertical fracturing and surface subsidence. [A further discussion follows of subsidence resulting from dissolution of brine to form drilling fluid} (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Liquid waste disposal

FEP Number (1.4.04.00.25)	**Originator FEP Description**: ... Disposal of liquid byproducts from oil and gas production involves injection of fluid into depleted reservoirs. Such fluid injection techniques result in repressurization of the depleted target reservoir and mitigates any effects of fluid withdrawal. The most significant effects of fluid injection would arise from substantial and uncontrolled leakage through a failed borehole casing. [Further discussion follows] (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Enhanced oil and gas production

FEP Number (1.4.04.00.26)	**Originator FEP Description**: ... Water flooding or hydraulic fracturing of oil- or gas-bearing units is used to improve the performance of hydrocarbon reservoirs in the Delaware Basin. ... CO2 injection is a tertiary oil recovery method, sometimes used in combination with water injection (the water alternating with gas method). [A lengthy discussion of enhanced recovery follows] (WIPP)

Primary: **Drilling Activities (Human Intrusion)**
Secondary: Hydrocarbon storage

FEP Number (1.4.04.00.27)	**Originator FEP Description**: Reinjection of gas for storage currently takes place in a depleted gas field in the Morrow Formation of the Delaware Basin. However, such injection techniques result in repressurization of the depleted target reservoir and mitigates any effects of fluid withdrawal. etc. (WIPP)

Primary: Effects of Drilling Intrusion

FEP Number (1.4.04.01.00)	**Primary Description:** Drilling activities that intrude into the repository may create new release pathways to the biosphere and alter existing pathways. Possible effects of a drilling intrusion include interaction with waste containers, increased saturation in repository leading to enhanced transport to the SZ, changes to groundwater and EBS chemistry, and waste brought to surface.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included* in the TSPA–SR for interaction and changes in condition / *Excluded* from the TSPA–SR for materials brought to the surface.	**Screening Decision Basis**: Does not satisfy a screening criterion / By Regulation
Number of Secondaries: 12	

Primary: **Effects of Drilling Intrusion**
Secondary: Drilling fluid interacts with waste

FEP Number (1.4.04.01.01)	**Originator FEP Description**: Water introduced into the unsaturated zone as drilling fluid by exploratory drillers drains downward, through the repository. (YMP)

Primary: **Effects of Drilling Intrusion**
Secondary: Drilling introduces surfactants

FEP Number (1.4.04.01.02)	**Originator FEP Description**: Surfactants introduced into the unsaturated rock by drilling fluids shift its characteristic curve, draining smaller pores around the borehole. Water introduced by subsequent infiltration events acts as though air were the wetting phase and flows through large pores and fractures. (YMP)

Primary: **Effects of Drilling Intrusion**
Secondary: Direct exposure to waste in mud pit

FEP Number (1.4.04.01.03)	**Originator FEP Description**: Drilling requires use of large amounts of fluid which is currently handled on the surface by use of pits or ponds. Contaminated cuttings are brought to the surface and deposited in the mud pit. (YMP)

Primary: **Effects of Drilling Intrusion**
Secondary: Flooding of drifts with drilling fluids

FEP Number (1.4.04.01.04)	**Originator FEP Description**: Drillers whose borehole intersects a drift are likely to experience a drill string drop and loss of circulation as drilling fluid flows into the void space. While drilling fluid losses can be substantial, a driller responds to loss of circulation by putting stemming material down the hole and grouting and if all else fails abandoning the hole. (YMP)

Primary: **Effects of Drilling Intrusion**
Secondary: Drilling fluid flow

FEP Number (1.4.04.01.05)	**Originator FEP Description**: ... Borehole fluid flow during drilling could result in hydrological or geochemical disturbances of the disposal system and could affect radionuclide transport. Such drilling-related FEPs could influence groundwater flow and potentially, radionuclide transport in the affected areas. (WIPP)

Primary: **Effects of Drilling Intrusion**
Secondary: Drilling fluid loss

FEP Number (1.4.04.01.06)	**Originator FEP Description**: Borehole circulation fluid could be lost to thief zones encountered during drilling. Such a drilling-related FEP could influence groundwater flow, and potentially, radionuclide transport in the affected units. (WIPP)

Primary: **Effects of Drilling Intrusion**
Secondary: Blowouts

FEP Number (1.4.04.01.07)	**Originator FEP Description**: ... Naturally occurring brine and gas pockets have been encountered during drilling in the Delaware Basin. Brine pockets have been intersected in the Castile and in the Salado above the WIPP horizon. Gas blowouts have occurred during drilling the Salado. ... Potentially, the most significant disturbance to the disposal system could occur if an uncontrolled blowout during drilling resulted in substantial flow through the borehole from a pressurized zone to a thief zone. etc. (WIPP)

Primary: **Effects of Drilling Intrusion**
Secondary: Drilling-induced geochemical changes

FEP Number	Originator FEP Description
(1.4.04.01.08)	**Originator FEP Description**: [This FEP discusses a number of diverse changes: movement of brine from a pressurized zone to a thief zone, changes in colloid formation, changes to sorption, drilling fluid loss, etc.] (WIPP)

Primary: **Effects of Drilling Intrusion**
Secondary: Fluid injection-induced geochemical changes

FEP Number	Originator FEP Description
(1.4.04.01.09)	**Originator FEP Description**: Injection of fluids through a leaking borehole could affect the geochemical conditions in thief zones, such as the Salado interbeds or the Culebra. Such fluid injection-induced geochemical changes could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area through their effects on colloid transport and sorption. [Further discussion follows] (WIPP)

Primary: **Effects of Drilling Intrusion**
Secondary: Cuttings

FEP Number	Originator FEP Description
(1.4.04.01.10)	**Originator FEP Description**: In accordance with the requirements of 40 CFR 194.33(b)(1), the DOE models consequences of inadvertent and intermittent intrusion into the repository during drilling for natural resources as the most severe human intrusion scenario that may affect long-term performance of the disposal system. (WIPP)

Primary: **Effects of Drilling Intrusion**
Secondary: Cavings

FEP Number	Originator FEP Description
(1.4.04.01.11)	**Originator FEP Description**: In accordance with the requirements of 40 CFR 194.33(b)(1), the DOE models consequences of inadvertent and intermittent intrusion into the repository during drilling for natural resources as the most severe human intrusion scenario that may affect long-term performance of the disposal system. ... Second, cavings, which contain material eroded from the borehole by the circulating drill fluid, may also be brought to the surface by the circulating drill mud. [A lengthy discussion of drilling is given] (WIPP)

Primary: **Effects of Drilling Intrusion**
Secondary: Spallings

FEP Number	Originator FEP Description
(1.4.04.01.12)	**Originator FEP Description**: ... Spallings are the particulate material introduced into the drilling mud by the movement of gas from the waste into the borehole annulus. [A lengthy discussion of 'Spallings' and how this problem is treated is included] (WIPP)

Primary: Mining and Other Underground Activities (Human Intrusion)

FEP Number	Primary Description
(1.4.05.00.00)	**Primary Description**: Mining and other underground human activities (e.g., tunneling, underground construction, quarrying) could disrupt the disposal system.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis**: By Regulation
Number of Secondaries: 21	

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Mine shaft intersects waste container

FEP Number (1.4.05.00.01)	**Originator FEP Description**: Builders of a mine shaft intercept a waste container and bring radioactive waste up with the mine waste. This is not an intentional retrieval and the waste container is not recognizable as such (an intact, 100 tonne container would be somewhat difficult to raise up a shaft, in any case). (YMP)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: A mine shaft creates a preferential path through the upper non-welded unit and a wetter zone develops

FEP Number (1.4.05.00.02)	**Originator FEP Description**: A mine shaft creates a preferential path through the upper nonwelded unit and a wetter zone develops in the Topopah Spring welded unit. (YMP)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Intrusion (mining)

FEP Number (1.4.05.00.03)	**Originator FEP Description**: Intrusion into the disposal system could occur through the construction of a mine downgradient of the vault or near the vault. Possible effects include changes to groundwater flow regimes, rock integrity and transport pathways. The critical group might be the miners. (AECL)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Mines

FEP Number (1.4.05.00.04)	**Originator FEP Description**: Mines constructed in the vicinity of the disposal vault could affect groundwater flow regimes, rock integrity and transport pathways (AECL)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Solution mining

FEP Number (1.4.05.00.05)	**Originator FEP Description**: Solution mining or other new mining techniques might be used near the vault, affecting flow regimes, transport pathways and/or rock properties. (AECL)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Water from mining above the repository drains through the repository

FEP Number (1.4.05.00.06)	**Originator FEP Description**: Water introduced in mining above the repository, drains downward through the repository. (YMP)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Underground dwellings

FEP Number (1.4.05.00.07)	**Originator FEP Description**: There is a possibility that future generations might use relatively easy accessible underground facilities as dwellings. The use of a repository site would of course only come in question if the knowledge of the repository is lost. etc. (Joint SKI/SKB)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Resource mining

FEP Number	Originator FEP Description: (none) (NEA)
(1.4.05.00.08)	

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Tunneling

FEP Number	Originator FEP Description: (none) (NEA)
(1.4.05.00.09)	

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Underground construction

FEP Number	Originator FEP Description: (none) (NEA)
(1.4.05.00.10)	

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Quarrying, near surface extraction

FEP Number	Originator FEP Description: (none) (NEA)
(1.4.05.00.11)	

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Mining activities

FEP Number	**Originator FEP Description**: The crystalline basement of Northern Switzerland has no known mineral resources that are likely to attract mining activities. etc. (NAGRA)
(1.4.05.00.12)	

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Potash mining

FEP Number	**Originator FEP Description**: Potash can be extracted either by underground excavation or by solution mining. etc. (WIPP)
(1.4.05.00.13)	

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Other resources

FEP Number	
(1.4.05.00.14)	**Originator FEP Description**: Potash is the only known economically viable resource in the vicinity of WIPP that is recovered by underground mining. Excavation for other resources does take place elsewhere in the Delaware Basin. In numerous areas, sand, gravel, and caliche are produced. These activities have not altered the geology of the controlled area significantly, and have been eliminated from performance assessment calculations based on low consequence to the performance of the disposal system. (WIPP)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Tunneling

FEP Number	
(1.4.05.00.15)	**Originator FEP Description**: ... Excavation activities that can cause underground disturbances include mining, tunneling, construction of underground storage or disposal facilities, and archaeological investigations. ... Consistent with the future states assumptions in 40 CFR 194.25(a), excavation activities that have not taken place in the Delaware Basin over the past 100 years need not be included in consideration of future human activities. etc. (WIPP)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Construction of underground facilities

FEP Number	
(1.4.05.00.16)	**Originator FEP Description**: ... Excavation activities that can cause underground disturbances include mining, tunneling, construction of underground storage or disposal facilities, and archaeological investigations. ... Consistent with the future states assumptions in 40 CFR 194.25(a), excavation activities that have not taken place in the Delaware Basin over the past 100 years need not be included in consideration of future human activities. etc. (WIPP)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Archaeological excavations

FEP Number	
(1.4.05.00.17)	**Originator FEP Description**: ... Excavation activities that can cause underground disturbances include mining, tunneling, construction of underground storage or disposal facilities, and archaeological investigations. ... Consistent with the future states assumptions in 40 CFR 194.25(a), excavation activities that have not taken place in the Delaware Basin over the past 100 years need not be included in consideration of future human activities. etc. (WIPP)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Deliberate mining intrusion

FEP Number	
(1.4.05.00.18)	**Originator FEP Description**: Consistent with 40 CFR 194.33(b)(1), all near-future and future human-initiated FEPs relating to deliberate mining intrusion into the WIPP excavation have been eliminated from performance assessment calculations on regulatory grounds. (WIPP)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Heat storage in lakes or underground

FEP Number (1.4.05.00.19)	**Originator FEP Description**: Although currently quite unimportant on the Shield, lakes and underground materials could be used for storing large amounts of heat. This in itself may influence the behavior and transport of contaminants in the environment, but there would also have to be a circulating medium, such as water, to recover the heat. (AECL)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Changes in groundwater flow due to mining

FEP Number (1.4.05.00.20)	**Originator FEP Description**: ... Excavation activities may result in hydrological disturbances of the disposal system. Subsidence associated with excavations may affect groundwater flow patterns through increased hydraulic conductivity within and between units. (WIPP)

Primary: **Mining and Other Underground Activities (Human Intrusion)**
Secondary: Changes in geochemistry due to mining

FEP Number (1.4.05.00.21)	**Originator FEP Description**: ... Excavation activities may result in hydrological disturbances of the disposal system. Fluid flow associated with excavation activities may also result in changes in brine density and geochemistry in the disposal system. (WIPP)

Primary: Explosions and Crashes (Human Activities)

FEP Number (1.4.11.00.00)	**Primary Description:** Explosions or crashes resulting from future human activities may affect the long-term performance of the repository. Explosions may result from nuclear war, underground nuclear testing or resource exploitation.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis**: By Regulation
Number of Secondaries: 9	

Primary: **Explosions and Crashes (Human Activities)**
Secondary: Bomb blast

FEP Number (1.4.11.00.01)	**Originator FEP Description**: Nuclear or conventional bombs exploded over the vault may alter rock properties and flow regimes. (AECL)

Primary: **Explosions and Crashes (Human Activities)**
Secondary: Collisions, explosions, and impacts

FEP Number (1.4.11.00.02)	**Originator FEP Description**: A variety of disasters might happen that could compromise the integrity of the disposal system; an aircraft could crash on the earth's surface above the vault; a nuclear device could be detonated near the vault during testing or in a war; a large meteorite may strike near the vault, open it and disperse its contents over a wide area. (AECL)

Primary: **Explosions and Crashes (Human Activities)**

Secondary: Underground test of nuclear devices

FEP Number	
(1.4.11.00.03)	**Originator FEP Description**: This FEP is connected to J6.7, nuclear war, and the intended intrusion events (J5.5,J5.33,J5.34,J5.35,J5.37). It is obvious that a underground test of a nuclear device close to a repository may seriously disturb both the engineered and the geological barrier. [This FEP, which continues with a sociological assessment which is flawed in its assumptions, also presumes too much about the extent of consequences of testing] (Joint SKI/SKB)

Primary: **Explosions and Crashes (Human Activities)**
Secondary: Explosions

FEP Number	
(1.4.11.00.04)	**Originator FEP Description**: This FEP concerns explosions coupled to sabotage. (Joint SKI/SKB)

Primary: **Explosions and Crashes (Human Activities)**
Secondary: Nuclear war

FEP Number	
(1.4.11.00.05)	**Originator FEP Description**: ... nuclear war implies unintended actions (bomb explosions) against the repository. Intended actions (e.g., sabotage with nuclear device) are more harmful and would create similar(but worse) type of damage. (Joint SKI/SKB)

Primary: **Explosions and Crashes (Human Activities)**
Secondary: Underground nuclear testing

FEP Number	
(1.4.11.00.06)	**Originator FEP Description**: (none) (NEA)

Primary: **Explosions and Crashes (Human Activities)**
Secondary: Explosions for resource recovery

FEP Number	
(1.4.11.00.07)	**Originator FEP Description**: ... Subsurface explosions associated with resource recovery and underground nuclear device testing may result in pathways for fluid flow between hydraulic conductive horizons. ... Neither small -scale nor regional-scale explosive techniques to enhance formation hydraulic conductivity form a part of current oil- and gas- production technology. etc. (WIPP)

Primary: **Explosions and Crashes (Human Activities)**
Secondary: Underground nuclear device testing

FEP Number	
(1.4.11.00.08)	**Originator FEP Description**: ... Subsurface explosions associated with underground nuclear device testing may result in pathways for fluid flow between hydraulic conductive horizons. ... The criterion in 40 CFR 194.32(a), relating to the scope of performance assessments, limits the consideration of future human actions to mining and drilling. Therefore, future underground nuclear device testing has been eliminated from performance assessment calculations on regulatory grounds. (WIPP)

Primary: **Explosions and Crashes (Human Activities)**

Secondary: Changes in groundwater flow due to explosions

FEP Number (1.4.11.00.09)	**Originator FEP Description**: ... The small-scale explosions that have been used in the Delaware Basin to fracture oil-and natural-gas-bearing units to enhance resource recovery have been too deep to have disturbed the hydrology of the disposal system. etc. (WIPP)

Primary: Meteorite Impact

FEP Number (1.5.01.01.00)	**Primary Description:** Meteorite impact close to the repository site might disturb or remove rock so that radionuclide transport to the surface is accelerated. Possible effects include alteration of flow patterns (faults, fractures), changes in rock stress, cratering and exhumation of waste.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR for direct exhumation, and direct fracturing to the repository horizon / *Excluded* from the TSPA–SR for alteration of flow paths, fracturing of overlying geologic units, and for changes in rock stress.	**Screening Decision Basis:** Low probability / Low consequence to dose
Number of Secondaries: 4	

Primary: **Meteorite Impact**
Secondary: Meteorite Impact

FEP Number (1.5.01.01.01)	**Originator FEP Description**: Meteorite impact could cause activation, creation and sealing of faults, changes in topography, changes in rock stress and deformation of rock. (AECL)

Primary: **Meteorite Impact**
Secondary: Meteorite

FEP Number (1.5.01.01.02)	**Originator FEP Description**: "A review of probable meteorite impact craters in Europe was made and a total of 17 were found – including probable and possible occurrences. The probability of a large scale impact on the British mainland is approximately .006 per million years ... etc. (Joint SKI/SKB)

Primary: **Meteorite Impact**
Secondary: Meteorite Impact

FEP Number (1.5.01.01.03)	**Originator FEP Description**: (none) (NEA)

Primary: **Meteorite Impact**
Secondary: Impact of a large meteorite

FEP Number (1.5.01.01.04)	**Originator FEP Description**: Meteors frequently enter the earth's atmosphere, but most of these are small and burn up before reaching the ground. [A discussion of astroblemes and a derivation of the probability of disrupting the repository follow] (WIPP)

Primary: Extraterrestrial Events

FEP Number (1.5.01.02.00)	Primary Description: Extraterrestrial events (e.g., supernova, solar flare, gamma-ray buster, alien life forms) may affect long-term performance of the disposal system.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis**: Low consequence to dose
Number of Secondaries: 1	

Primary: Extraterrestrial Events
Secondary: Extraterrestrial Events

FEP Number (1.5.01.02.01)	Originator FEP Description: (none) (NEA)

Primary: Changes in the Earth's Magnetic Field

FEP Number (1.5.03.01.00)	Primary Description: Changes in the earth's magnetic field could affect the long-term performance of the repository.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis**: Low consequence to dose
Number of Secondaries: 3	

Primary: **Changes in the Earth's Magnetic Field**
Secondary: Flipping of the earth's magnetic poles

FEP Number (1.5.03.01.01)	Originator FEP Description: Flipping of the earth's magnetic poles could lead to temporary changes in the earth's ionization layer and increased solar radiation. (AECL)

Primary: **Changes in the Earth's Magnetic Field**
Secondary: Changes of the magnetic field

FEP Number (1.5.03.01.02)	Originator FEP Description: Even if there would be a change in the magnetic field it is hard to find any process that would impact the structure and function of the repository barriers. The working group has judged this FEP to have extremely low consequences for the repository. (Joint SKI/SKB)

Primary: **Changes in the Earth's Magnetic Field**
Secondary: Magnetic pole reversal

FEP Number (1.5.03.01.03)	Originator FEP Description: Reversal of the earth's magnetic poles could lead to a change in the earth's ionization layer, with subsequent evolution of the climate. (AECL)

Primary: Earth Tides

FEP Number (1.5.03.02.00)	**Primary Description:** Small changes of the gravitational field due to celestial movements (sun and moon) cause earth tides and may in turn cause pressure variations in the groundwater flow systems.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis:** Low consequence to dose
Number of Secondaries: 0	

Primary: Salt Creep

FEP Number (2.2.06.05.00)	**Primary 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.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis:** By Regulation
Number of Secondaries: 0	

Primary: Effects of Repository Heat on the Biosphere

FEP Number (2.3.13.03.00)	**Primary Description:** The heat released from radioactive decay of the waste will increase the temperatures at the surface above the repository. This could result in local or extensive changes in the ecological characteristics.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis:** Low consequence to dose
Number of Secondaries: 0	

Primary: Atmospheric Transport of Contaminants

FEP Number (3.2.10.00.00)	**Primary Description:** This category contains FEPs related to transport of contaminants in the atmosphere. Atmospheric transport includes radiotoxic and chemotoxic species in the air as gas, vapor, particulates or aerosol. Transport processes include wind, plowing and irrigation, degassing, saltation, and precipitation.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Included* in the TSPA–SR for transport mechanisms and species (via ashfall) / *Excluded* from the TSPA–SR for volatile radionuclides as a gaseous release through the host rock	**Screening Decision Basis:** Does not satisfy a screening criterion / Low consequence to dose
Number of Secondaries: 8	

Primary: **Atmospheric Transport of Contaminants**
Secondary: Suspension in air

FEP Number (3.2.10.00.01)	**Originator FEP Description**: There are a wide variety of pathways through which contaminants released from an underground vault could become suspended as particulates or gases in the atmosphere. The two major sources for suspension might be surface waters and soils, and many processes could be involved, such as degassing, wind erosion, plowing and irrigation. (AECL)

Primary: **Atmospheric Transport of Contaminants**
Secondary: Wind

FEP Number (3.2.10.00.02)	**Originator FEP Description**: Wind is a major environmental force in the dispersion of contaminants through soil erosion, and the transport of contaminants suspended in the atmosphere. etc. (AECL)

Primary: **Atmospheric Transport of Contaminants**
Secondary: Radionuclide volatilization / aerosol/ dust production

FEP Number (3.2.10.00.03)	**Originator FEP Description**: Radionuclides may be transported directly from he geosphere to the biosphere as gases and/or aerosols(if they are volatile). Radionuclide volatilization and/or aerosol production may also occur within the biosphere. (NAGRA)

Primary: **Atmospheric Transport of Contaminants**
Secondary: Convection, turbulence, and diffusion (atmospheric)

FEP Number (3.2.10.00.04)	**Originator FEP Description**: Airborne radionuclides can be directed, diluted and dispersed by convection, turbulence and diffusion. This in turn can strongly influence dose predictions for various organisms. (AECL)

Primary: **Atmospheric Transport of Contaminants**
Secondary: Deposition (atmospheric)

FEP Number (3.2.10.00.05)	**Originator FEP Description**: Airborne contaminants may settle on surfaces through wet and dry deposition. This can lead to contamination of vegetation, soil and surface water. etc. (AECL)

Primary: **Atmospheric Transport of Contaminants**
Secondary: Saltation

FEP Number (3.2.10.00.06)	**Originator FEP Description**: Saltation refers to the process by which soil particles become temporarily suspended into the atmosphere by wind action and then bounce along the soil surface. Thus, saltation can be an important factor in wind erosion and the dispersion of contaminants in the environment. (AECL)

Primary: **Atmospheric Transport of Contaminants**
Secondary: Atmosphere

FEP Number (3.2.10.00.07)	**Originator FEP Description**: The atmosphere is that part of the biosphere above the terrestrial and aquatic media (soil and surface water). Radionuclides may enter the atmosphere as gases (volatile radionuclides) or aerosols either because they have been transported from the geosphere in this form or they are generated within the biosphere. Radionuclides may also enter the atmosphere as particulates (dust, soil). (NAGRA)

Primary: **Atmospheric Transport of Contaminants**
Secondary: Precipitation (meteoric)

FEP Number (3.2.10.00.08)	**Originator FEP Description**: Rain, snow and other forms of precipitation may remove airborne contaminants and deposit them on various ground surfaces, including plants. This type of deposition, called wet deposition, can be important; it was a major determinant in the geographic distribution of the radionuclides injected into the atmosphere from the crippled Chernobyl reactor. (AECL)

Primary: Toxicity of Mined Rock

FEP Number (3.3.06.01.00)	**Primary Description:** Excavation of the repository and/or its contents may result in the production of tailings, which may subsequently release toxic contaminants.
Primary Assigned to: *System-Level FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis**: By Regulation
Number of Secondaries: 0	

ATTACHMENT IIA

DIAGENESIS

Bates and Jackson (1984, p. 137) define two types of diagenesis. Mineralogically, it is defined as "the geochemcial processes or transformations that affect clay minerals before burial in the marine environment." Sedimentologically, it is defined as "all the changes undergone by a sediment after its initial deposition, exclusive of weathering and metamorphism. It includes those processes (such as compaction, cementation, replacement) that occur under conditions of pressure and temperature that are normal in the outer portion of the earth's crust, and according to most U.S. geologists it includes changes occurring after lithification." Bates and Jackson (1984, p. 137) further state that "There is no universally accepted definition of the term, and no delimitation, e.g., with metamorphism." A prelithification definition has been used by Thrush (1968, p. 320) and Berry and Mason (1959, p. 233). Post-lithification changes in rock that change grain size, develop new minerals, or destroy previously existing minerals are typically considered to be alteration (Thrush 1968, p. 30) or metamorphism (Thrush 1968, p. 699) rather than diagenesis.

The majority of literature on diagenesis focuses on sedimentary deposits and diagenetic processes that have occurred in clastic or carbonate sedimentary environments. The history of the studied deposits is typically characterized as fluvial or marine deposition (either as clastic deposition or chemical precipitation) during and followed by an extended period of deep burial (<1000 meters). The geologic system at Yucca Mountain, however, is characterized by erosion and exhumation of lithified igneous materials, rather than deposition and burial of clastic or carbonate sedimentary sequences. Consequently, for the evaluation of Yucca Mountain FEPs, diagenesis is being expanded to include alteration of volcanic rocks at pressures and temperatures below metamorphic conditions, and lithification processes that may occur in surficial deposits.

The *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998, Section 6.1) provides an extensive discussion of diagenetic alteration of the volcanic rocks at Yucca Mountain. The host rock unit present at Yucca Mountain is a welded tuff. Diagenesis has altered rocks at Yucca Mountain in the past, and will continue to do so in the future. Diagenetic alteration has resulted in the formation of secondary zeolite and clay minerals. Much of this alteration occurred shortly after deposition of the volcanic rocks. Additional alteration has continued at a slower rate throughout the last 10 million years, subsequent to deposition of the tuffs. Note that the products of past diagenesis in the welded tuffs are included implicitly in the TSPA–SR through the assignment of models and parameters for flow and transport in the SZ and UZ.

Surficial Quaternary deposits occur at the Yucca Mountain site and in the region. These deposits result from the weathering of parent geologic material (rhyolitic tuffs), and subsequent erosion and redeposition. On Yucca Mountain, these surficial deposits are present as alluvial and colluvial fans and fan remnants and as deposits in stream channels. In the Amargosa Desert, they are present as valley-fill material. The primary lithification processes affecting these surficial deposits are compaction and cementation, which in turn decrease infiltration rates. The variance in infiltration rates based on soil types is currently incorporated into the infiltration models for the Yucca Mountain region.

The literature that describes diagenetic processes and the effects of diagenetic changes for surficial deposits in arid and semi-arid environments includes Krystinik (1990), Lattman (1973), Lattman and Simonberg (1971), Jacka (1974), and Reeves (1976).

Compaction/Consolidation

The primary diagenetic processes of concern for Yucca Mountain include compaction and cementation. Compaction due to burial can result in a significant decrease in porosity with time. Palmer and Barton (1987, Fig. 3 and p. 32) indicate that compaction due to burial of uncemented Tertiary-age sands reduced the in-situ porosity by about 12 to 13 percent of the initial porosity, while Berner (1980, Fig. 3.2) suggests a 40 to 50 percent decrease is possible, assuming a consistent and continuing burial process. Krystinik (1990, p. 8-2) indicates that the reduction of porosity in eolian deposits can be as much as 20 to 30 percent, depending on initial sorting, but adds that "compaction does not generally become an important factor in diagenesis until the onset of grain deformation and pressure solution during deeper burial diagenesis." (Krystinik. 1990, p. 8-3).

Cementation

A second diagenetic process is cementation. In most arid and semi-arid environments, cementation occurs due to formation of calcium carbonate or other carbonate cements (Reeves, 1976, p. 7; Lattman 1973, p. 3014). This may be expressed as formation of layers or a fracture infills in the near surface environment. However, the formation of carbonate cements is dependent on the presence of a source of the carbonate ion. Lattman (1973) conducted studies on fan deposits near Las Vegas, Nevada. The results indicate that alluvial fans in Nevada that consist of silicic igneous materials (such as those composed of rhyolite and rhyolitic tuffs) are "almost always very poorly cemented, showing little more than a few scattered, coated pebbles in weak calcic horizons. Even where, as in Las Vegas Basin, large quantities of calcareous dust are available, the cementation is very weak." Lattman (1973, p. 3022) Additionally, Lattman (1973, p. 3015) observed that "on rhyolite, rhyolitic tuff, and noncalcareous sediments, only pebble coatings or thin discontinuous stringers of calcareous cement are found."

Krystinik (1990, p. 8-8), however, discusses the role of other cementitious materials during diagenesis of surficial (eolian) deposits in arid environments, and also notes that weathering can reverse the previous effects of diagenesis by removing earlier cements and allowing deflation to occur (Krystinik 1990, p. 8-3). In the study of eolian deposits, Krystinik (1990, p. 8-4) indicates that in dry sand, diagenesis on the surface of active dunes occurs "in the form of minor chemical degradation of grains, rock-flour mortar, and as amorphous silica, iron, and aluminum oxy-hydroxide grain coatings" and also notes that observed cements in damp sand included amorphous iron silica, aluminum, and lesser percentages of calcite, smectite, and sodium carbonate. Krystinik (1990, as stated and inferred from p. 8-4, 8-8, and Table 2) also notes that the solutes in water associated with these cements are "remarkably similar" to examples of water from granitic/igneous source terranes documented by others.

Reeves (1976, p. 28) indicates that indurated soil horizons due to principally silica cementation are termed "duripans" in the U.S. and silcrete or silcrust in Australia and other countries. Reeves (1976, p. 29) also mentions that near-surface silica hardpans occur in granitic alluvium in the San Joaquin Valley, discusses the factors that favor silica verses carbonate cementation, and also mentions that many carbonate caliches contain measurable quantities of silica. Reeves (1976 p.

110) cites previous studies of caliche and other carbonate "hardpans" that indicate a significant reduction in vertical infiltration rates.

Duripans and/or petrocalcic layers are common in the soil descriptions provided in the draft Environmental Impact Statement (EIS) (DOE 1999, Table 3-19). It is possible that these deposits could experience additional cementation. Such cementation of deposits mantling Yucca Mountain could affect future rates of moisture infiltration or cementation in deposits composing the alluvial aquifer downgradient of Yucca Mountain. As indicated above, however, increases in cementation tend to decrease the porosity and permeability of deposits. Thus, it is unlikely that cementation will significantly increase infiltration or flow rates.

Rate of Diagenesis of Shallow Deposits

Lattman and Simonberg (1971 p. 277) indicate that "case-hardening" of vertical faces of carbonate alluvium and colluvium associated with run-off and in gullies can occur on the scale of a few years. Krystinik (1990, p. 8-1) comments that early cements in eolian deposits can precipitate in quantities to lithify sand to friable (i.e., poorly cemented) sandstone in less than 5,000 years. Humphrey et al. (1986, p 77 and 78) in their study of the diagenesis and carbonate cementations of the Smackover Formation of Louisiana indicate that "rates of mineralogic stabilization differ in the various diagenetic environments." For the materials studied on various carbonate islands, however, "mineralogic stabilization in the meteoric phreatic zone goes to completion within a few thousand years." They further state that rates of mineralogic stabilization in the shallow vadose zone (i.e., the downward limit of the zone of evapotranspiration) may be comparable to those of the meteoric phreatic environment. By contrast, Humphrey et al. (1986, p. 78) also cite studies from carbonate sequences that indicate incomplete diagenesis in the deep vadose zone even after 200,000 years.

Dependence on Climate

Reeves (1976, p. 84-87) indicates that the ideal environment for caliche formation appears to be neither excessively arid nor excessively humid, and that caliche formation can occur over a wide range of climatic conditions. Reeves (1976, p. 86) further states that:

> Certainly, the vast mineralogical differences between calcium carbonate and silica, yet the juxtaposition of both minerals in caliche, is prima facia evidence of significant changes in soil chemistry... Because soil chemistry is affected by so many variables, such as temperature, parent material, vegetation, time and topography, it is impossible to describe a singular causative environmental factor for caliche formation.

Birkeland (1974, p. 234) and Reeves (1976, Fig 4-10) cite studies that suggest that the depth to calcareous horizons (i.e., pedocals) is closely related to the amount and timing of precipitation. Increased precipitation generally results in a greater depth to the calcic horizon.

ATTACHMENT IIB

METEORITE IMPACT AND CRATERING PROBABILITY

Various authors have calculated the probability of impact of known individual interplanetary bodies with the earth's atmosphere. Chyba (1993, Table 1a) addresses 12 objects with diameters of less than 50 m that have been observed to date. Excluding object 1991 VG (a suspected possible human artifact), the mean calculated probability of impact on the earth's atmosphere for the known bodies is 1 per 29 gigayears, or approximately 10^{-5} in 10,000 years. Marsden and Steel (1994, p. 235, Figure 4) provide the calculated atmospheric-impact probabilities, defined as within 0.1 to 1 astronomical unit (AU) (1 AU = 149,598,000 kilometers) for all observed long period comets (i.e., orbit duration of greater than 200 years). The greatest calculated probability is 2.6×10^{-7} per orbit and the estimated mean impact probability is 2×10^{-9} to 3×10^{-9} per orbit. These probabilities are for any impact on the earth's atmosphere. If one neglects atmospheric shielding effects, the probability of impact for any square kilometer of the earth's surface can be estimated by dividing the above probabilities by 5.2×10^{8} km^2, the approximate surface area of the earth. Since impact is a spatially random process (Grieve 1987, p. 257), the greatest probability (2.6×10^{-7} per orbit) of impact divided by the earth's surface area yields a probability of approximately 5×10^{-16} per orbit per km^2. The probability of the impact of any individual, known object is, therefore, considerably less than the regulatory threshold of 10^{-4} in 10,000 years or an equivalence of about 10^{-8} annual recurrence probability.

However, the probability of meteorite impact must also be examined over the range of the possible objects (i.e., for the entire flux, not just for individual known objects) and the probability must include consideration of only those objects which will actually create a crater above or near the repository. The impact cratering rate is dependent on several factors including the flux and composition of meteoroids into earth's atmosphere, the initial conditions of entry (mass, velocity, angle), and the size of craters resulting from impact of meteorite fragments. The probability of a meteorite impact crater being of sufficient size to affect the repository performance is also directly related to the physical dimensions of the repository (particularly the depth below surface) and the mechanism proposed for impacts affecting the repository (i.e., direct exhumation, fracturing to repository depth, or creation of surface depressions).

Cratering Rates

Based on a review of available literature, three possible methods for determining cratering rates were examined. These methods include rates proposed by Neukum and Ivanov (1994), the distribution determined by Grieve (1987) based on terrestrial impact structures (Assumption 5.5.1 of this document, ANL-WIS-MD-000019), and the calculation of rates using cumulative meteoroid flux data (various sources) combined with the work on impact cratering parameters done by Hills and Goda (1993) (Assumption 5.5.1 of this document, ANL-WIS-MD-000019).

Neukum and Ivanov (1994)

Neukum and Ivanov (1994, Table IV) provide a tabulation of impact accumulation rates and mean time intervals between impacts, for earth, based on lunar data and adjusted for gravity differences. This table includes the mean interval between events with energies equal to or greater than that required to form a crater of a given diameter. The cumulative cratering rate (or frequency) of such events can be derived from the calculated mean intervals by using the inverse of the mean interval. The frequency per square kilometer of the earth's surface can be derived by dividing the frequency by the area of earth's surface. This calculation is provided as Table IIB-1, and the results are plotted on Figure IIB-1. This curve represents an extreme upper bound for the cratering rate on earth, as it accounts for gravity differences between the lunar and earth surfaces and includes data for small diameter craters. However, it does not take into account atmospheric shielding effects, which are known to exist.

Grieve (1987)

A more applicable cumulative cratering rate (and more commonly used for these types of analysis – see Assumption 5.5.1 of this document, ANL-WIS-MD-000019) can be derived from Grieve (1987). The number of impact craters larger than a crater diameter D, produced per year per square km is proportional to the apparent crater diameter to the –1.8 power (Grieve, 1987, p. 257, and Figure 8; Assumption 5.5.1 of this document, ANL-WIS-MD-000019):

$$F(D) \propto D^{-1.8} \qquad \text{(Eq. 1)}$$

where F(D) is equal to the number of craters larger than a given diameter, produced per year per square km, as a function of diameter, D.

Putting

$$F(D) = K\,D^{-1.8} + B, \qquad \text{(Eq. 2)}$$

values for K and B can be derived from available data. The constant B is zero since F(D) goes to zero as the crater diameter (D) becomes very large. Grieve (1995, p. 196) fixes F(D) for D = 20 km at $(5.5 \pm 2.7) \times 10^{-15}/\text{km}^2/\text{yr}$ (Assumption 5.5.1 of this document, ANL-WIS-MD-000019).

So from Eq.2:

$$F(20) = K(20)^{-1.8} = (5.5 \pm 2.7) \times 10^{-15}/\text{km}^2/\text{yr},$$

which allows a value to be assigned to K,

$$K = (1.2 \pm 0.6) \times 10^{-12.} \qquad \text{(Eq. 3)}$$

The crater diameter value of 20 km was chosen because the plot of F(D) versus D becomes convex as D decreases below 20 km, Grieve (1987, p. 257) notes that "at smaller diameter the distribution falls off". The decrease is interpreted to be due to increased ease of obscuration of craters, by weathering and tectonic processes, as the crater diameter gets smaller. The limitation of this distribution is effectively for craters with diameters exceeding approximately 10 km (Neukum and Ivanov, 1994, p. 404). For the purposes of this analysis, however, the distribution will be extended to the 1 meter size. Although this introduces an increased uncertainty in the cratering rate for small diameter (i.e., less than 10 km) craters, it is at least based on observed earth (as opposed to lunar) data. The derived values for this distribution are provided in Table IIB-2, and the corresponding frequency curve is also shown on Figure IIB-1.

Using the Fundamental Theorem of Calculus, and the definition of F(D), a distribution function for the frequency of impact for craters of a given diameter D can be found.

By definition:

$$F(D) = \int_0^{\infty} f(x)dx = KD^{-1.8}$$

Therefore:

$$f(D) = 1.8\,K\,D^{-2.8}. \qquad \text{(Eq. 4)}$$

Equation 4 will be used later in determining the frequency of impact cratering in the repository area.

<u>Cratering Rates Derived From Cumulative Flux Data</u>

The direct application of the Neukum and Ivanov cratering distribution is limited because it does not consider atmospheric shielding), and the Grieve's distribution is limited because it is applicable for large diameter craters, but questionable for small diameter craters. Consequently, to determine probabilities of meteorite-impact cratering damage, a cratering diameter distribution curve was developed based on data for the cumulative flux of interplanetary bodies and masses that have been studied during the 1980's and 1990's. The flux and size data was applied against known atmospheric shielding effects, and the effective cratering distribution was determined (Assumption 5.5.1 of this document, ANL-WIS-MD-000019).

Flux of Material

Ceplecha (1992, p. 362) has compiled flux data from a variety of authors for masses ranging from 10^{-21} to 10^{15} kg (46 orders of magnitude). This compilation is provided in graphical form (Ceplecha 1992, Figure 1) as the log of the mass (m) to the log of the cumulative number (N) of interplanetary bodies of a mass equal to or greater than m coming to the earth's atmosphere every year.

The present analysis of probability, however, is only concerned with the range of bodies capable of creating craters in the earth's surface. Select values from this graph over the potential range of interest are provided in Table IIB-3, which describes the flux of material coming to the entire earth's atmosphere (Assumption 5.5.1 of this document, ANL-WIS-MD-000019). It does not address the nature of the material, its velocity, atmospheric shielding effects, the frequency and size of material actually impacting the earth's surface, nor the resulting impact crater size.

Mass and Initial Radii of Meteoroids

As defined by Chapman and Morrison (1994, p. 34) and by Shoemaker (1983, p. 464), meteor composition is described as metallic (iron to iron-nickel, and relatively rare), stony (mixtures of iron and stony material, chondritic–type S asteroids), or cometary (low-density silicates, organics and volatiles–type C asteroids). The term carbonaceous is also used for those bodies that lie between stony and cometary bodies. The total range in bulk densities can vary from 8 g/cm^3 to less than 1 g/cm^3 for the metallic and cometary materials respectively (Chapman and Morrison, 1994, p.34). Ceplecha (1994, p. 967, Table 1 and Table 3) suggests densities of 3.7 g/cm^3 for stony material, 2.0 g/cm^3 for carbonaceous materials, and <1 to 1.1 g/cm^3 for cometary material. For this analysis, the assumed densities will be 8 g/cm^3 for metallics, 3.7 g/cm^3 for stony materials and 1.1 g/cm^3 for carbonaceous/cometary materials (Assumption 5.5.2 of this document, ANL-WIS-MD-000019). By using the flux values from Ceplecha (1992), described above and presented in Table IIB-3, and assuming spherical meteoroids with the density values listed above, the corresponding radius by meteoroid composition can be calculated. The mass (m) of a sphere is:

$$m = (4/3\ \pi\ r^3)(\rho)$$

where:

m = mass (g)
ρ = density (g/cm$^{3)}$
r = radius (cm)

and correspondingly:

$$r = (m / (4/3\ \pi)(\rho))^{1/3} \qquad \text{(Eq. 5)}$$

The initial radii of meteors by mass and by composition are provided in Table IIB-4.

Atmospheric Shielding Effects

Upon entering the earth's atmosphere, a meteor is subject to multiple destructive processes including ablation and fragmentation caused by heating and differential stresses. These processes tend to dissipate energy into the atmosphere. The magnitude of the atmospheric dissipation of energy is a function of the radius and composition of the body, the initial entry velocity, and the angle of the entry. Hills and Goda (1998, p. 228) provide a series of figures which show the fraction of energy dissipated into the atmosphere for various radii of meteors. The dissipation of energy is such a significant effect that, for a certain range of radii and initial velocities, the energy dissipation may be total and no surface impact occurs.

The range of values bracketing this atmospheric shielding window varies depending on the composition of the meteor. Various authors provide different estimates of the threshold size and velocity. Ceplecha (1992, p. 364) indicates atmospheric shielding is completely effective for stony bodies below a mass of 10^5 kg, for carbonaceous bodies below 10^7 kg, and for cometary bodies below 10^{11} kg. Ceplecha (1994, p. 969) also indicates that "only stony bodies with low initial velocities (less than 20 km/sec) and larger than 8 m can reach the surface with impact velocities larger than 4 km/sec giving rise to an explosive crater." Chapman and Morrison (1994, p. 33) indicate that "most projectiles less than 50 m in diameter, with energies less than approximately 10 megatons dissipate the energy harmlessly in the upper atmosphere." This is based on analysis of a stony object with an initial impact velocity of 20 km/sec. Hills and Goda (1993, p. 1142) indicate that the threshold corresponds to a critical radius of 100m for a stony asteroid, and 500 m for a comet. For iron meteoroids with initial velocities of 20 km/sec, the critical radius is 20-30 m; however, for initial velocities of 11.2 - 15 km/sec the critical radius is lowered to about 2 m. Hills and Goda (1993, p. 1140) indicate that craters with radii of approximately 50 to100 m can be formed by meteors with initial radii of 1 to 5 m, if the initial velocity is below 15 km/sec. Hills and Goda (1998) further refine the thresholds based on the angle of entry. However, there is no indication in the literature of the frequency of occurrence of these low velocity events.

There is no direct statistical information available on the distribution of velocities for interplanetary bodies by composition or size. Initial velocities for long period comets are approximately 15 to 80 km/sec (Marsden and Steel 1994, p 233-236). Short period comets have initial velocities of 30-40 km/sec (Chapman and Morrison, 1994, p. 34). Hills and Goda (1993, p. 1140) analyzed impact cratering scenarios using initial velocities ranging from 11.2 km/sec to 30.0 km/sec. The initial velocities for 11 known objects with diameters from 7 to 55 m provided by Chyba (1993, Table 1a, and excluding object 1991 VG, a suspected human artifact) range from 12.9 to 21.2 km/sec. Ceplecha (1994, Table 2) provides initial velocities of 14 observed bodies with diameters between 1 and 10 m. The velocities of known objects are summarized in Table IIB-5.

The present analysis will consider cratering rates for assumed initial velocities of 15 and 20 km/sec for all meteors regardless of composition or size (Assumption 5.5.3 of this document, ANL-WIS-MD-000019). These values are at the lower end of the range of velocities specified by various authors. Given that lower initial values generally yield larger impact craters (Hills and Goda 1993, Figure 17), the assumption of velocities of 15 and 20 km/sec is a conservative assumption and will tend to slightly overestimate the probability of craters of a given size. It is also consistent with the assumptions used in the existing literature. As shown in Table IIB-5, the average initial velocity of objects of 1 to 10 m diameter is 20.7 km/sec, while for larger objects it is 15.8 km/sec.

Also, this analysis will consider that all objects enter the atmosphere at zenith angle zero, and could potentially yield surface impacts (Assumption 5.5.4 of this document, ANL-WIS-MD-000019). This is a conservative assumption, since objects entering at nonzero zenith angles have more kinetic energy absorbed (Hills and Goda, 1998). There are no data available relating flux and angle of entry .

Cratering Frequency Based on Cumulative Flux Data

A frequency curve can be derived based on the cumulative flux data previously discussed. This analysis uses the calculated meteor radii for the various meteor compositions (see Table IIB-4), assumed initial velocities of 15 and 20 km/sec, the modeling results provided in Hills and Goda (1993, Fig 17), and assumptions about the relative percentage by composition of the total cumulative flux data (Assumption 5.5.5 of this document, ANL-WIS-MD-000019).

The modeling work by Hills and Goda (1993, Fig 17) relates initial meteor radius and initial velocity to the radius of the impact crater produced by the largest fragment (or the residual meteorite). Table IIB-6 provides the relationship between meteor composition, initial meteor radii, initial velocity, and resulting crater radius. It was derived from the curves in Hills and Goda (1993, Figs. 16 and 17) by selecting the velocity curve and initial meteor radius, and reading the corresponding point for the resulting crater radius.

The relative percentage of the total cumulative flux by composition is not known with any measurable precision. Ceplecha (1992, p. 361) states that bodies in the mass range of 10^{12} and 10^{15} kg are mostly stony or carbonaceous bodies, and in the range of 10^{4} to 10^{7} kg they are mostly inactive comets. Ceplecha (1994, Figure 2) also provides a plot of the percent of stony bodies in this size range; the percentages vary from 2 percent at the 10 m diameter size to approximately 18 percent at the 0.1 m diameter. Chyba (1993, p. 703) notes that iron-nickel comprises about 6 percent of observed main-belt asteroids and about an equal fraction of Earth-crossing asteroids. He also speculates, however, that if objects are lunar in origin, the iron-nickel objects may be entirely absent. In addressing small impact craters from iron meteorites, Shoemaker (1983, p. 480) states as an assumption that "... the fraction of iron objects of any given energy is 0.015 to 0.03 . . . ." Hills and Goda (1998, p. 225) quote Shoemaker as verbally providing a value for the frequency of iron impactors of any given size of "3.5 percent of that of stones". For this analysis, it will be assumed that a maximum of 3.5 percent of the total flux is metallic in nature.

For this analysis, the frequency of iron impactors is assumed to be 3.5 percent of the total flux. Down to an initial meteor mass of approximately 10^{8} kg (radius of 18.6 m for stony and 27.9 for carbonaceous), the remaining flux was divided between stony and carbonaceous material. For initial meteor masses below 10^{8} and down to 10^{-1} kg (minimum radius of 0.02 m for stony material and 0.03 m for carbonaceous material), the stony material is presumed to constitute between 2 to 18 percent of the flux depending on initial meteor radii. The remainder is attributable to carbonaceous material (see Assumption 5.5.5 of this document, ANL-WIS-MD-000019).

The difficulty with relating the impact events by mass (Table IIB-3) to a probability is that for a given initial velocity, meteors of equal initial radius but differing compositions result in different crater diameters. In addition, meteors with different initial radius but the same composition can result in equal crater diameters. A method was needed to determine the number of impact events resulting in crater diameter "D" by composition. And a method was needed and to sum the number of possible events resulting in crater diameter "D" regardless of meteor composition or radius of the initial meteor.

The number of impact events caused by a meteorite of a given composition and producing a crater diameter "D" or larger was determined from the data provided in Tables IIB-3, IIB-6, and the relative percentage of the cumulative flux attributed to each composition (Assumption 5.5.5

of this document, ANL-WIS-MD-000019). The mass of the initial meteor and the total number of impact events per year for the total cumulative flux were taken from Table IIB-3. The total number of events by mass was then multiplied by the relative percent composition to give the number of events by mass for a given meteor composition. Through the mass term, the data from Table IIB-6 was used to relate the cumulative number of events by mass and composition to the resulting crater radius for initial velocities of 15 and 20 km/sec (Assumption 5.5.3 of this document, ANL-WIS-MD-000019). The crater radius was then doubled to account for diameter. These calculations are shown in Tables IIB-7a, IIB-7b, and IIB-7c.

A graphical method was chosen to sum the number of cratering events of diameter "D" or larger. Using the data presented in Tables IIB-7a, IIB-7b, and IIB-7c, the number of events per year by mass and composition was plotted against the resulting crater diameter for initial velocities of 15 km/sec and 20 km/sec, as presented in Figures IIB-2 and IIB-3. Once the three compositions were plotted, the cumulative number of cratering events was read for each composition for a range of crater diameters from 0.001 km to 10 km. These values were entered in Tables IIB-8a and IIB-8b. Because the individual composition curves were multi-valued for a given diameter, up to three columns were needed, each representing a different portion of the curve. The cumulative number of events per year for a given diameter and velocity was found by summing the number of events from the individual composition curves and entered into Table IIB-8a and IIB-8b. The cumulative number of events for each diameter was then divided by the surface area of the earth to derive the total frequency/km^2 curve. The individual composition curves and the resulting total frequency/km^2 curves are provided on Figures IIB-2 and IIB-3 for 15 km/sec and 20 km/sec initial velocities, respectively. The total frequency/km^2 curves are also shown on Figure IIB-1 for comparison to the distribution curves derived from Neukum and Ivanov (1994) and Grieve (1987).

Probability Of Craters of a Given Diameter

Figure IIB-1 represents the range of possible frequencies of impacts resulting in a given or larger crater diameter. All frequency curves fall below the Neukum and Ivanov curve. This is to be expected since the curve derived from Neukum and Ivanov (1994, Table IV) is based on the lunar cratering rate and neglects any atmospheric shielding effects. The Neukum and Ivanov frequencies were not used in the probability calculations, since they would severely overestimate the frequency of occurrence. The curve derived from Grieve is based on extrapolation of observable earth cratering data, but its limitation is for crater diameters larger than 10 km. For this analysis, however, the Grieve distribution was assumed to be constant for the smaller crater diameters. The curves derived from the cumulative flux data are highly dependent on the assumptions regarding composition, in as much as initial radius is related to assumed densities, and on assumptions about the relative composition of the cumulative flux. This is especially true where impacts due to iron meteorites comprise the majority of the craters (i.e., in the crater diameter range of approximately 10 to 100 m for initial velocities of 15 km/sec). The cumulative flux curves overstate the frequency of impact resulting in a given crater diameter if the relative percent of iron meteorites is lower and/or the percent of carbonaceous meteorites is greater than that assumed. Also, these curves likely conservatively overstate the frequency because it is assumed that the entire flux enters earth's atmosphere at angles that result in the least atmospheric dissipation.

The frequency curve derived from the Grieve distribution and the cumulative flux distributions were used in calculation of the frequency for the repository area and for the outcrop area. The two sets of calculations were required because of the different areas of the targets. The target immediately overlying the repository is assumed to be 8.6 km by 1.3 km, and the outcrop area is assumed to be 1.1 km by 0.1 km (Assumption 5.5.6 of this document, ANL-WIS-MD-000019). However, if a meteorite were to impact exterior to the repository boundary or outcrop area but within 1/2 of the crater diameter from the boundary, the repository could still potentially be impacted. This affects the boundaries on each side of the repository and the outcrop. Assuming that fracturing and exhumation effects are cylindrical below the entire crater (Assumption 5.5.9 of this document, ANL-WIS-MD-000019), the target area can be expressed as:

$$\text{Area (A)} = (L + 2 \text{ x } D/2)(W + 2 \text{ x } D/2) = (L+D)(W+D),$$

which simplifies to

$$\text{Area (A)} = LW \text{ x } (L+W)D \text{ x } D^2 \quad \text{(Eq. 6)}$$

Where:

L = length of target area (km)
W = width of target area (km)
D = diameter of crater(km)

The overall annual probability of meteorite impacts that could disrupt or fracture the repository is thus given by the product of the frequency of impact and the target area integrated over the ranges of possible crater diameters:

$$N = \int f(D) A\,dD \quad \text{(Eq.7)}$$

From Equation 4 and Equation 6, and with k = power of the distribution for a given meteorite crater distribution:

$$N = \int(-k\,K\,D^{k-1})(LW + (L+W)D + D^2)dD$$

By removing the constants k and K and using the additive properties of integrals, the resulting integral is in the form of $\int u^n\,du$

$$N = -kK\int(LWD^{k-1} + (L+W)D^k + D^{k+1})dD \quad \text{(Eq. 8)}$$

The integrations will be bounded at the lower end by the crater diameter capable of resulting in a given type of damage, and the upper bound will be assumed to be 300 km - or the largest suspected crater diameter on the earth's surface (Grieve 1995, Table 1: Vredefort Crater, South Africa).

Equation 8 simplifies to:

$$N = -k\,K \left[\frac{LW(D)^{k}}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right]_{D}^{300} \qquad \text{(Eq. 9)}$$

Where:

N = frequency of impacts per year capable of disrupting the repository
K = the proportionality constant (from regression analysis)
k = power of the distribution (from regression analysis)
L = length of the repository
W = width of the repository
D = diameter of the crater

The length (L) and width (W) variables were set at L = 8.6 km and W = 1.3 km for the maximum area of repository (See CRWMS M&O 2000b), and as L=1.1, W=0.1 for the Paintbrush outcrop area above the repository area (see DOE, 1998, Figure 2.8) (Assumption 5.5.6 of this document, ANL-WIS-MD-000019).

The power of -1.8 shown in Equation 4, and the value for K of $(1.2 \pm 0.6) \times 10^{-12}$ shown for Equation 3 are only applicable to the Grieve's distribution. Tables IIB-9a through IIB-9d provide the results of the regression analyses for the cumulative flux distributions, i.e., for the upper and lower portions of the frequency curves for 15 km/sec and 20 km/sec respectively. Because of the offset in the cumulative-flux-derived frequency curves, the constant K was also determined for each portion of the curve.

Tables IIB-10a, IIB-10b, and IIB-10c provide the annual probability calculations for cratering above the repository, and in Tables IIB-11a, IIB-11b, and IIB-11c provide the annual probability for cratering in the outcrop area. Annual probability curves for the repository and for the outcrop area for the Paintbrush nonwelded tuff are provided on Figures IIB-4 and IIB-5 respectively. Figures IIB-4 and IIB-5 are plotted as the annual probability to allow for assumption of any desired time period. Assuming a uniform distribution, the probability in 10,000 years is obtained by multiplying the cited probability by a factor of 10^4. The regulatory threshold of 10^{-4}/10,000 years corresponds to 10^{-8} on the referenced figures.

Relation of Crater Diameter to Depths of Concern

There are two impact effects that could theoretically affect repository performance. Direct exhumation could occur if cratering exhumes material below the top of the repository. Fracturing of the geologic units above the repository is also of concern. Fracturing could potentially create a direct release pathway if the repository were breached by fractures, or could result in increased infiltration into the repository.

For this analysis, a repository depth of 250 m was assumed as an upper bounding condition (see Assumption 5.5.6 of this document, ANL-WIS-MD-000019).

Direct exhumation from cratering occurs to depths corresponding to a minimum of 10 percent and a maximum of 30 percent of the crater surface diameter (Wuschke et al. 1995, p. 3; Dence et al. 1977, p. 250; Grieve 1987, p. 248 – see Assumption 5.5.7 of this document, ANL-WIS-MD-000019). For a repository depth of 250 m (Assumption 5.5.6 of this document, ANL-WIS-MD-000019), the threshold crater diameters (D) for direct exhumation could range from as high as 2,500 m for the 10 percent case, and as low as 830 m for the 30 percent case. Given that smaller diameter craters occur more frequently than large diameter crater, the probability of particular interest is that associated with the 830 m crater.

Direct fracturing from the surface to the repository depth is also considered. The depth of the fracture zone below a crater can be estimated from models of attenuation of a hemispherical shock wave, expressed as a function of inverse powers of distance from the shock point (Dence et al. 1977, pp. 261-263). Dence et al. (1977) determine the depth of fracturing - to - crater diameter to have the relationship of $R = 0.45D$ to $R = 0.36D$. Wuschke et al. (1995, p.3) indicates, however, that the depth of fracture in plutonic rock for simple craters could be as high as 0.76 of the crater diameter. Given a range of factors from 0.36 to 0.76 (see Assumption 5.5.8 of this document, ANL-WIS-MD-000019), and assuming a repository depth of 250 m (Assumption 5.5.6 of this document, ANL-WIS-MD-000019), the crater diameters which might result in direct fracturing of the repository range from as low as 328 m (using the extreme factor of 0.76) to 500 m (using the conservative value of 0.5) to as large as 700 m (using a minimal factor of 0.36).

Fracturing is also of concern with regards to the potential for increased infiltration rates, even if direct fracturing to repository depth is not a factor. The Paintbrush nonwelded tuff unit plays an important role in reducing water flow downward into the repository (DOE, 1999, p. 3-46). To significantly affect percolation rates at the repository horizon, the impact would need to significantly increase fractures through the Paintbrush nonwelded tuff units.

The Paintbrush nonwelded tuff is typically overlain by approximately 60 to 100 m of material, except where it outcrops on the western flanks of Yucca Mountain. In the outcrop areas, adjacent to the waste emplacement area, the unit thickness is between 20 and 100 meters (DOE 1998, Figures 2-8 and 2-9). Consequently, the depths of interest are 60 to 100 m over the bulk of the repository and 20 meters where the thinnest portion of the unit may be exposed in outcrop above the repository. Assuming fracture depths of 0.36 to 0.76 of the crater diameter (Assumption 5.5.8 of this document, ANL-WIS-MD-000019), the threshold crater diameters of potential interests range from approximately 78 m (using the extreme factor of 0.76) to 277 m over the repository area (using the minimal factor of 0.36), and 26 (using the extreme factor of 0.76) to 55 m (using the minimal factor of 0.36) in the outcrop area.

Consideration of Threshold Crater Diameter to Screening Criteria

From Figure IIB-4, it is readily observable that direct exhumation, direct fracturing of the repository, and fracturing of the Paintbrush Unit above the repository are low probability events and need not be considered.

Figure IIB-5 provides the frequency of impacts occurring in the Paintbrush outcrop area above the repository. At the threshold probability of 10^{-4}/10,000 years (10^{-8} frequency), only the crater diameters indicated by the curves for the cumulative flux (v = 15 km/sec) exceed the upper bounding diameter. At the 10^{-8} annual frequency, the v=15 km/sec crater diameter is approximately 80 m. Fracturing through the thin outcrop could occur if the depth of fracturing to crater diameter exceeds a ratio of 0.25. The crater diameter for the v=20 km/sec corresponds with the lower bounding diameter of 25m, but the frequency from the Grieve's distribution is significantly less that threshold crater diameter and corresponds to a diameter of about 2 meters.

An 80-meter diameter crater encompasses an area of approximately .005 km^2 compared to the total repository area of 11.1 km^2, or approximately 0.04 percent of the land surface above the repository. Because of the outcrop's location along the westward edge of the repository and the minimal land surface affected, additional fracturing would not significantly alter the unsaturated zone flow conditions within the waste emplacement area. Additionally, two of the three distributions (Grieve's and the v = 20 km/sec) indicate that cratering of sufficient diameter to cause the fracturing is a low probability event and could be excluded based on probability. Fracturing of the outcrop area is *Excluded* based on low consequence to dose.

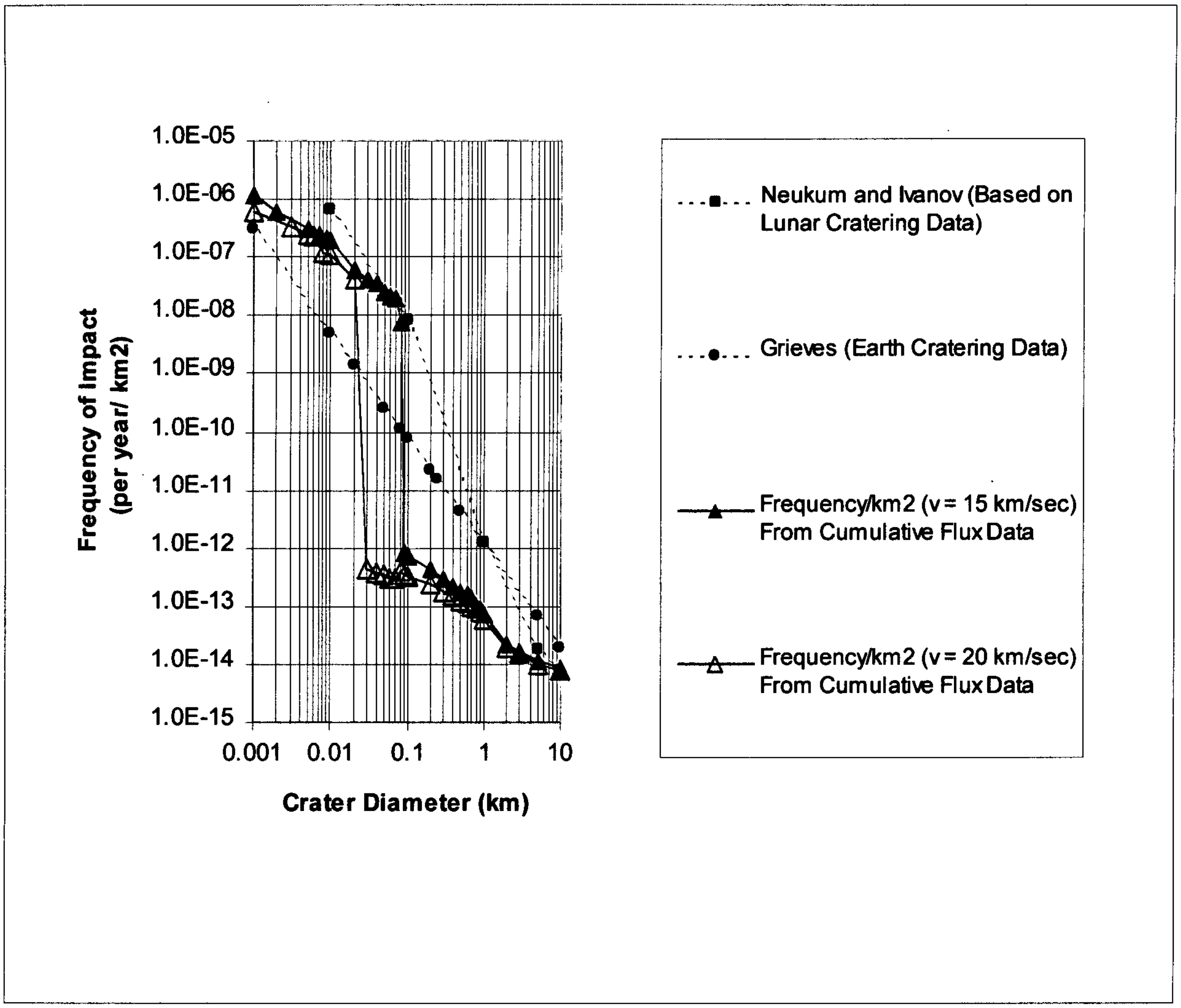

Figure IIB-1 Frequency of Cratering Events on the Earth's Surface

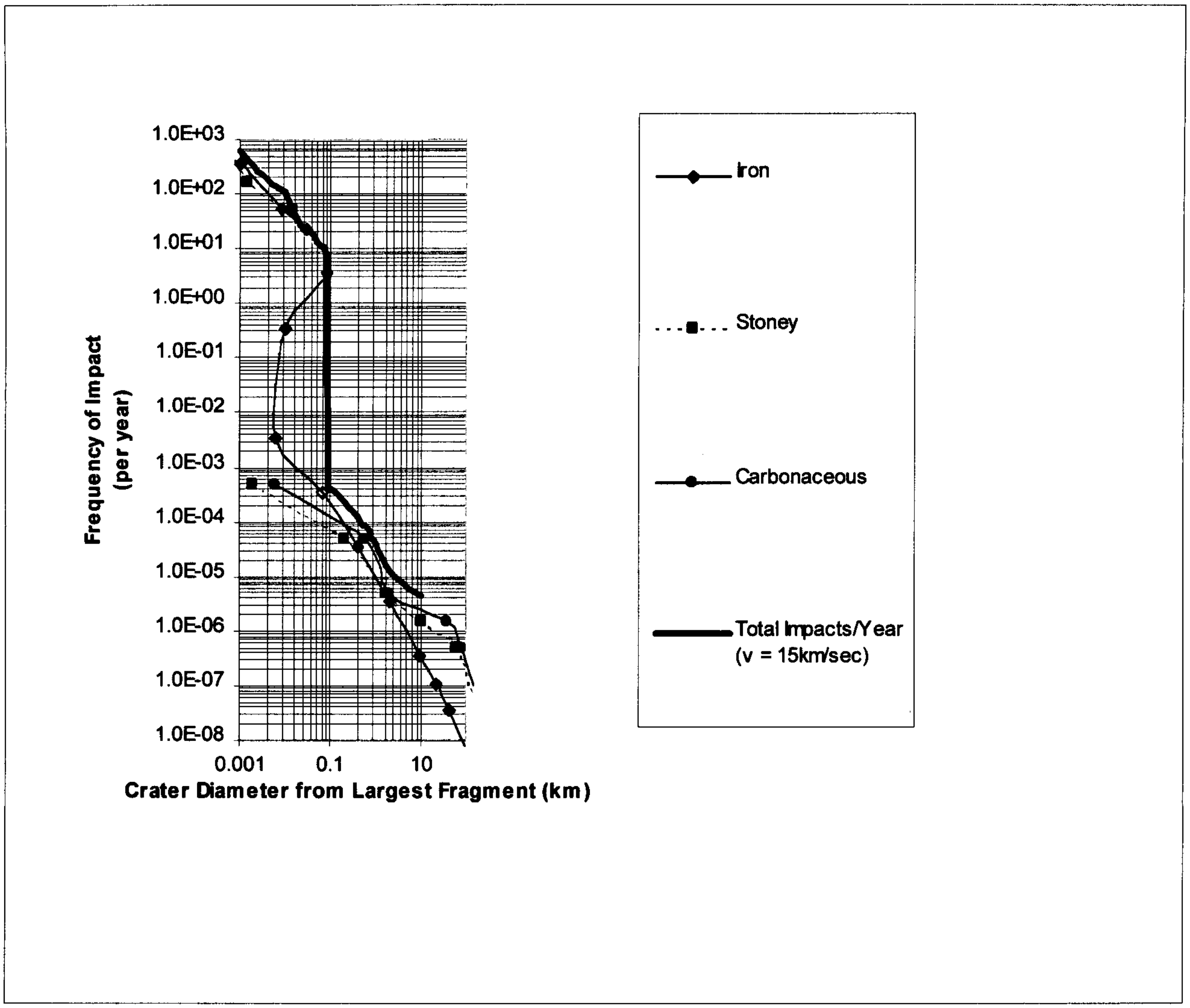

Figure IIB-2 Total Number of Cratering Events Per Year ($V_{initial}$ = 15 km/sec)

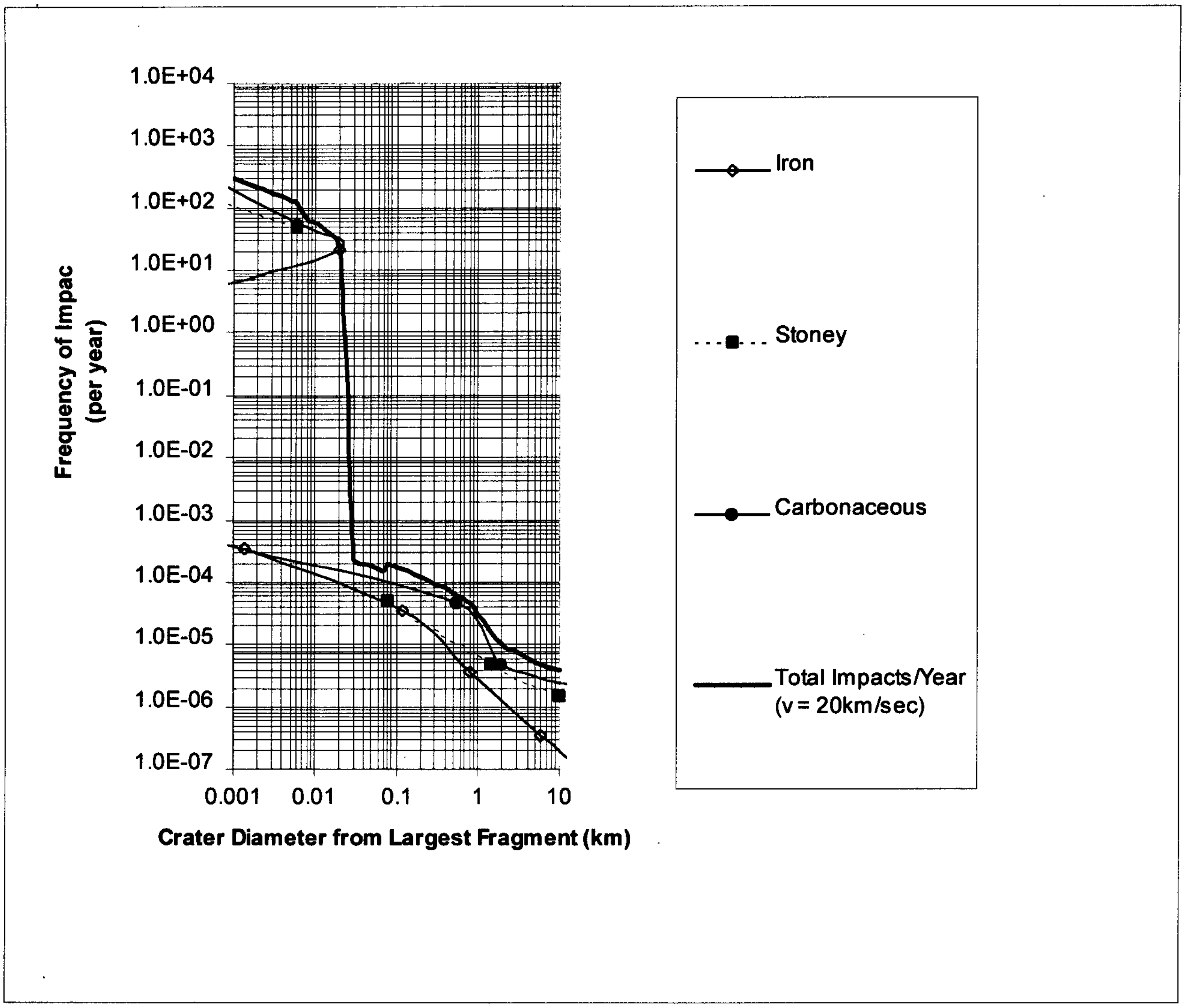

Figure IIB-3 Total Number of Cratering Events Per Year ($V_{initial}$ = 20 km/sec)

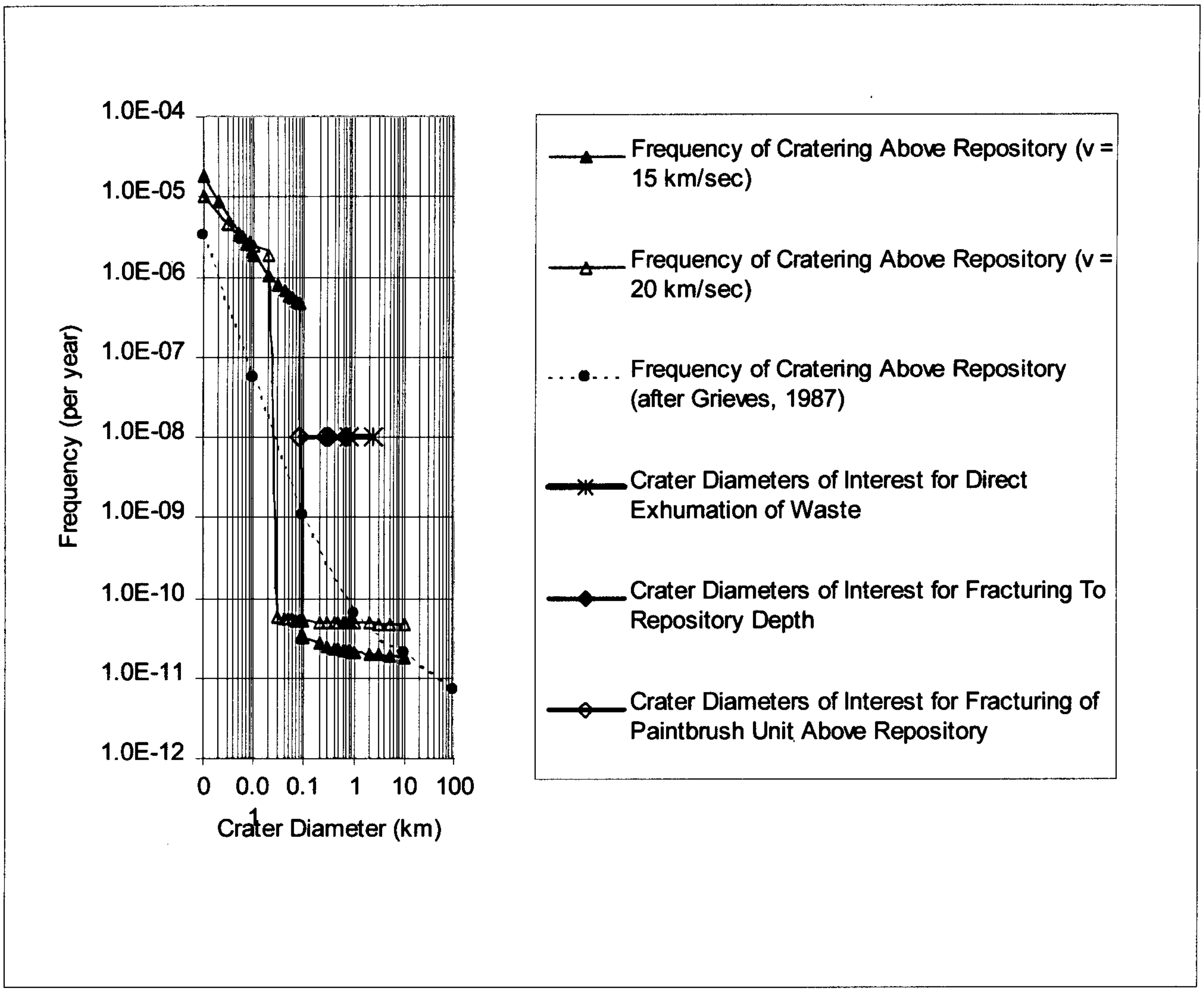

Figure IIB-4 Frequency of Cratering Events Above the Repository

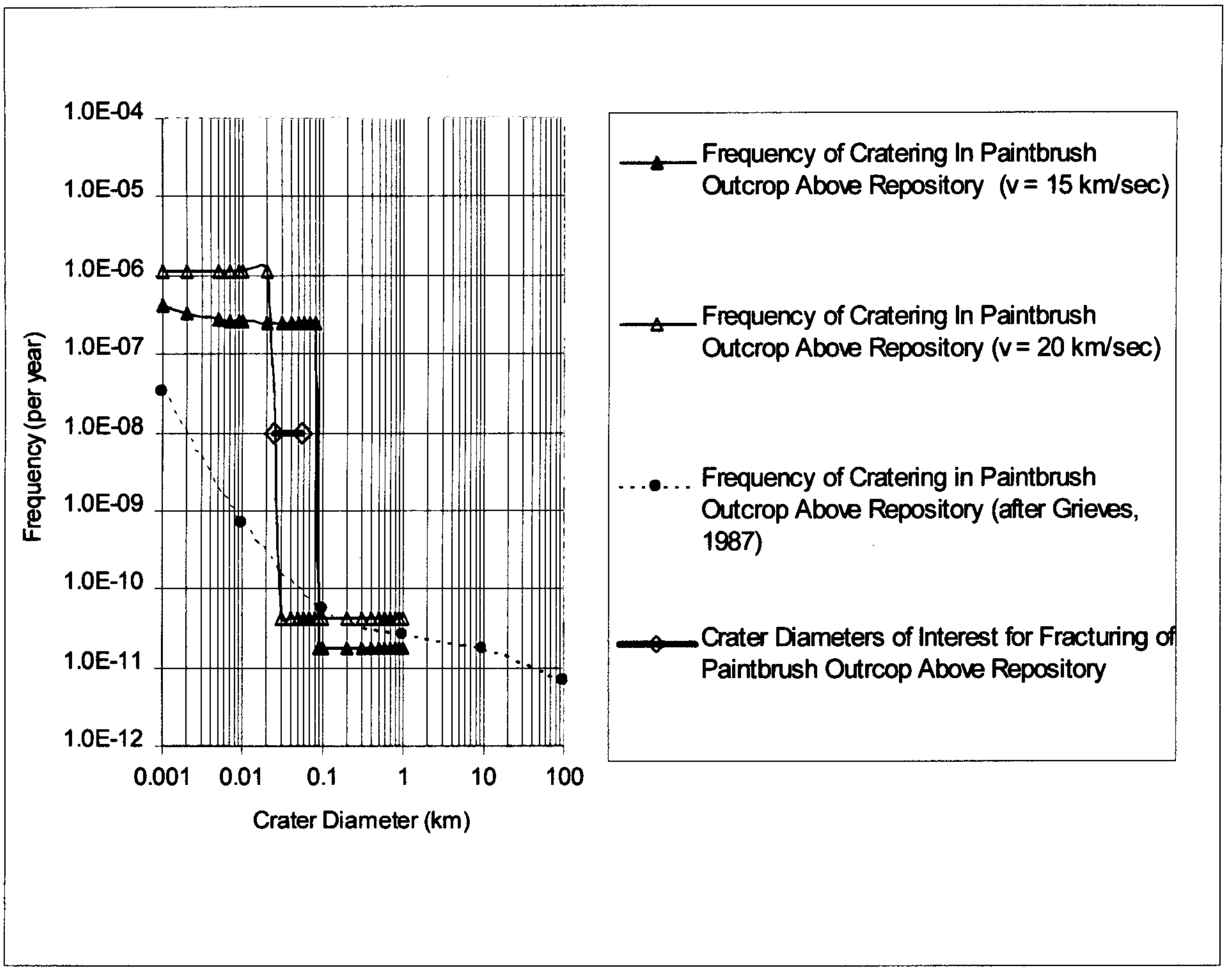

Figure IIB-5 Frequency of Cratering Events in the Paintbrush Nonwelded Tuff Outcrop Area

Table IIB-1. Cratering Impact Frequencies on Earth Based on Lunar Impact Crater Data

Crater Diameter (km)	Mean Interval Between Events (yr)	Frequency(whole earth) (Events per year)	Frequency / km^2 (Events per year / km^{-2})
10	2.58×10^{5}	3.88×10^{-6}	7.50×10^{-15}
5	1.10×10^{5}	9.09×10^{-6}	1.76×10^{-14}
1	1.60×10^{3}	6.25×10^{-4}	1.21×10^{-12}
0.1	2.41×10^{-1}	4.15×10^{0}	8.03×10^{-9}
0.01	3.00×10^{-3}	3.33×10^{2}	6.45×10^{-7}

Notes:
Data are from Neukum and Ivanov (1997, Table IV) and are for a cratering event of given diameter or larger
Earth Surface Area assumed as 5.17×10^8 km^2

Table IIB-2 Cratering Impact Frequencies on Earth Based on Earth Impact Crater Data

Crater Diameter (km)	D (km)	$D^{-1.8}$	Frequency (Events per yr/ km^2) K x ($D^{-1.8}$)
10	10	0.0158	1.9×10^{-14}
5	5	0.0552	6.6×10^{-14}
1	1	1	1.2×10^{-12}
0.5	0.5	3.482	4.2×10^{-12}
0.25	0.25	12.13	1.5×10^{-11}
0.2	0.2	18.11	2.2×10^{-11}
0.1	0.1	63.09	7.6×10^{-11}
0.08	0.08	94.28	1.1×10^{-10}
0.05	0.05	219.7	2.6×10^{-10}
0.02	0.02	1143	1.4×10^{-9}
0.01	0.01	3981	4.8×10^{-9}
0.001	0.001	251190	3.0×10^{-7}

Notes:
Based on Grieve (1987)
$K = 1.2 \times 10^{-12}$

Table IIB-3 Cumulative Flux of Material Entering Earth's Atmosphere

Log of Mass (m) (kg)	Log of N (Events of Mass (m) or larger/year)	Mass (kg)	Events/year (N)
15	-7.5	1.00×10^{15}	3.16×10^{-08}
14	-7	1.00×10^{14}	1.00×10^{-07}
13	-6	1.00×10^{13}	1.00×10^{-06}
12	-5.5	1.00×10^{12}	3.16×10^{-06}
11	-5	1.00×10^{11}	1.00×10^{-05}
10	-4	1.00×10^{10}	1.00×10^{-04}
9	-3	1.00×10^{9}	1.00×10^{-03}
8	-2	1.00×10^{8}	1.00×10^{-02}
7	-1	1.00×10^{7}	1.00×10^{-01}
6	1	1.00×10^{6}	1.00×10^{1}
5	2	1.00×10^{5}	1.00×10^{2}
4	2.8	1.00×10^{4}	6.31×10^{2}
3	3.2	1.00×10^{3}	1.58×10^{3}
2	4	1.00×10^{2}	1.00×10^{4}
1	4.2	1.00×10^{1}	1.58×10^{4}
0	5	1.00×10^{0}	1.00×10^{5}
-1	5.5	1.00×10^{-1}	3.16×10^{5}

Notes:

Values for (m) and (N) selected manually from Ceplecha (1992, p. 362, Figure 1)

Table IIB-4. Mass and Radius by Meteor Composition Based on Cumulative Flux Data

Mass (kg) (from Table IIB-3)	Initial Radius of Meteor (meters) (Composition and Assumed Density)		
	Iron 8 g/cm^3	Stony 3.7 g/cm^3	Carbonaceous 1.1 g/cm^3
1.00×10^{15}	3102	4010	6009
1.00×10^{14}	1440	1862	2789
1.00×10^{13}	668	864	1294
1.00×10^{12}	310	401	601
1.00×10^{11}	144	186	279
1.00×10^{10}	66.8	86.4	129
1.00×10^{9}	31.0	40.1	60.1
1.00×10^{8}	14.4	18.6	27.9
1.00×10^{7}	6.68	8.64	12.9
1.00×10^{6}	3.10	4.01	6.01
1.00×10^{5}	1.44	1.86	2.79
1.00×10^{4}	0.668	0.864	1.29
1.00×10^{3}	0.310	0.401	0.601
1.00×10^{2}	0.144	0.186	0.279
1.00×10^{1}	0.067	0.086	0.129
1.00×10^{0}	0.031	0.040	0.060
1.00×10^{-1}	0.014	0.019	0.028

Notes:

Based on mass being contained in a spherical asteroid of a given density

Densities based on Ceplecha 1994, Table 1 and Table 3, and Chapman and Morrison 1994, p. 34

Table IIB-5. Velocity of Observed Objects

Data Source	Diameter (1 - 10 m)	Velocity (km/sec)	Diameter (11 - 60m)	Velocity (km/sec)
Chyba (1993, Table 1a)	8	13.7	- -	- -
Ceplecha (1994, Table 2)	1.3	14.6	- -	- -
Ceplecha (1994, Table 2)	10	15.08	- -	- -
Ceplecha (1994, Table 2)	2.2	15.7	- -	- -
Ceplecha (1994, Table 2)	1.3	16.1	- -	- -
Ceplecha (1994, Table 2)	1.1	19.2	- -	- -
Ceplecha (1994, Table 2)	1.8	20.886	- -	- -
Ceplecha (1994, Table 2)	1.9	21.086	- -	- -
Ceplecha (1994, Table 2)	2.6	21	- -	- -
Chyba (1993, Table 1a)	7	21.2	- -	- -
Ceplecha (1994, Table 2)	2	23.6	- -	- -
Ceplecha (1994, Table 2)	1.9	23.8	- -	- -
Ceplecha (1994, Table 2)	1	24.6	- -	- -
Ceplecha (1994, Table 2)	1.2	26.5	- -	- -
Ceplecha (1994, Table 2)	1.4	27	- -	- -
Ceplecha (1994, Table 2)	7.1	27	- -	- -
Chyba (1993, Table 1a)	- -	- -	36	12.9
Chyba (1993, Table 1a)	- -	- -	44	13.3
Chyba (1993, Table 1a)	- -	- -	17	13.9
Chyba (1993, Table 1a)	- -	- -	28	13.9
Chyba (1993, Table 1a)	- -	- -	28	15.7
Chyba (1993, Table 1a)	- -	- -	26	16.5
Chyba (1993, Table 1a)	- -	- -	44	17.8
Chyba (1993, Table 1a)	- -	- -	55	18.6
Chyba (1993, Table 1a)	- -	- -	18	19.3
Average		20.7		15.8
Median		21.0		15.7

Table IIB-6. Initial Meteor Radius and Crater Radius Resulting from Largest Fragment

Initial Meteor Mass (kg) (from Table IIB-3)	**Iron (Density: 8 g/cm^3)**		**Stony (Density: 3.7 g/cm^3)**		**Carbonaceous (Density: 1.1 g/cm^3)**	
	Initial Meteor Radius (m) (from Table IIB-4)	**Crater Radius (m) 15 km/sec / 20 km/sec**	**Initial Meteor Radius (m) (from Table IIB-4)**	**Crater Radius (m) (15 km/sec / 20 km/sec)**	**Initial Meteor Radius (m) (from Table IIB-4)**	**Crater Radius (m) (15 km/sec / 20 km/sec)**
1.00×10^{15}	3102	170,000 / 200,000	4010	170,000 / 200,000	6009	210,000 / 300,000
1.00×10^{14}	1440	70,000 / 90,000	1862	70,000 / 90,000	2789	100,000 / 130,000
1.00×10^{13}	668	22,000 / 22,000	864	30,000 / 40,000	1294	43,000 / 70,000
1.00×10^{12}	310	11000/ 9000	401	5000 / 5000	601	20,000 / 28,000
1.00×10^{11}	144	4500 / 3000	186	800 / 700	279	1,000 / 1000
1.00×10^{10}	66.8	1000 / 400	86.4	100 / 40	129	280 / 280
1.00×10^{9}	31.0	200/ 60	40.1	1 / Shielding Effect	60.1	3 / 0.2
1.00×10^{8}	14.4	32 / 0.7	18.6	Shielding Effect	27.9	Shielding Effect
1.00×10^{7}	6.68	3.2 / Shielding Effect	8.64	Shielding Effect	12.9	Shielding Effect
1.00×10^{6}	3.10	5 / Shielding Effect	4.01	Shielding Effect	6.01	Shielding Effect
1.00×10^{5}	1.44	40 / 0.1	1.86	Shielding Effect	2.79	Shielding Effect
1.00×10^{4}	0.668	14 / 10	0.864	7 / 3	1.29	Shielding Effect
1.00×10^{3}	0.310	4 / 3	0.401	0.75 / 0.32	0.601	Shielding Effect
1.00×10^{2}	0.144	0.6 / 0.2	0.186	0.17 / 0.1	0.279	0.2 /Shielding Effects
1.00×10^{1}	0.067	0.1 / 0.1	0.086	0.1 / Shielding Effect	0.129	0.1 / Shielding Effects
1.00×10^{0}	0.031	Off-scale	0.040	Off-scale	0.060	Off-scale
1.00×10^{-1}	0.014	Off-scale	0.019	Off-scale	0.028	Off-scale

Notes:

Crater radius from manual selection of initial meteor radius and crater radius at various velocities from Hills and Goda (1993, Figs 16 (shaded) and 17).

Table IIB-7a. Frequency of Crater Impact Events Based on Cumulative Flux and Composition: Iron Meteors

Total Events / Year (for Total Cumulative Flux)	Initial Meteor Mass (kg)	Fraction of Cumulative Flux	Number of Events per Year for Iron Meteors	Crater Radius (m) (for 15 km/sec)	Crater Diameter (km) (for 15 km/sec)	Crater Radius (m) (for 20 km/sec)	Crater Diameter (km) (for 20 km/sec)
3.16×10^{-08}	1.00×10^{15}	0.035	1.1×10^{-9}	170,000	340	200,000	400
1.00×10^{-07}	1.00×10^{14}	0.035	3.5×10^{-9}	70,000	140	90,000	180
1.00×10^{-06}	1.00×10^{13}	0.035	3.5×10^{-8}	22,000	44	22,000	44
3.16×10^{-06}	1.00×10^{12}	0.035	1.1×10^{-7}	11,000	22	9,000	18
1.00×10^{-05}	1.00×10^{11}	0.035	3.5×10^{-7}	4500	9	3,000	6
1.00×10^{-04}	1.00×10^{10}	0.035	3.5×10^{-6}	1000	2	400	0.800
1.00×10^{-03}	1.00×10^{9}	0.035	3.5×10^{-5}	200	0.400	60	0.120
1.00×10^{-02}	1.00×10^{8}	0.035	3.5×10^{-4}	32	0.064	0.7	0.0014
1.00×10^{-01}	1.00×10^{7}	0.035	3.5×10^{-3}	3.2	0.006	Shielding Effect	Shielding Effect
1.00×10^{1}	1.00×10^{6}	0.035	3.5×10^{-1}	5	0.001	Shielding Effect	Shielding Effect
1.00×10^{2}	1.00×10^{5}	0.035	3.5×10^{0}	40	0.080	0.1	0.0002
6.31×10^{2}	1.00×10^{4}	0.035	2.2×10^{1}	14	0.028	10	.020
1.58×10^{3}	1.00×10^{3}	0.035	5.5×10^{1}	4	0.008	3	.006
1.00×10^{4}	1.00×10^{2}	0.035	3.5×10^{2}	0.6	0.001	0.2	.0004
1.58×10^{4}	1.00×10^{1}	0.035	5.5×10^{2}	0.1	0.0002	0.1	.0002
1.00×10^{5}	1.00×10^{0}	0.035	3.5×10^{3}	Off-scale	Off-scale	Off-scale	Off-scale
3.16×10^{5}	1.00×10^{-1}	0.035	1.1×10^{4}	Off-scale	Off-scale	Off-scale	Off-scale

Table IIB-7b. Frequency of Crater Impact Events Based on Cumulative Flux and Composition: Stony Meteors

Total Events / Year for Total Cumulative Flux	Initial Meteor Mass (kg)	Fraction of Cumulative Flux	Number of Events per Year for Stony Meteors	Crater Radius (m) (for 15 km/sec)	Crater Diameter (km) (for 15 km/sec)	Crater Radius (m) (for 20 km/sec)	Crater Diameter (km) (for 20 km/sec)
3.16×10^{-08}	1.00×10^{15}	0.485	1.5×10^{-8}	170,000	340	200,000	400
1.00×10^{-07}	1.00×10^{14}	0.485	4.9×10^{-8}	70,000	140	90,000	180
1.00×10^{-06}	1.00×10^{13}	0.485	4.9×10^{-7}	30,000	60	40,000	80
3.16×10^{-06}	1.00×10^{12}	0.485	1.5×10^{-6}	5000	10	5000	10
1.00×10^{-05}	1.00×10^{11}	0.485	4.9×10^{-6}	800	1.6	700	1.4
1.00×10^{-04}	1.00×10^{10}	0.485	4.9×10^{-5}	100	0.200	40	.080
1.00×10^{-03}	1.00×10^{9}	0.485	4.9×10^{-4}	1	.002	Shielding Effect	Shielding Effect
1.00×10^{-02}	1.00×10^{8}	0.485	4.9×10^{-3}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
1.00×10^{-01}	1.00×10^{7}	0.02	2.0×10^{-3}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
1.00×10^{1}	1.00×10^{6}	0.04	4.0×10^{-1}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
1.00×10^{2}	1.00×10^{5}	0.06	6.0×10^{0}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
6.31×10^{2}	1.00×10^{4}	0.08	5.0×10^{1}	7	.014	3	0.006
1.58×10^{3}	1.00×10^{3}	0.10	1.6×10^{2}	0.75	.0015	0.32	0.0006
1.00×10^{4}	1.00×10^{2}	0.14	1.4×10^{3}	0.17	.00034	0.1	0.0002
1.58×10^{4}	1.00×10^{1}	0.18	2.8×10^{3}	0.1	.0002	Shielding Effect	Shielding Effect
1.00×10^{5}	1.00×10^{0}	0.16	1.6×10^{4}	Off-scale	Off-scale	Off-scale	Off-scale
3.16×10^{5}	1.00×10^{-1}	0.16	5.1×10^{4}	Off-scale	Off-scale	Off-scale	Off-scale

Table IIB-7c. Frequency of Crater Impact Events Based on Cumulative Flux and Composition: Carbonaceous Meteors

Total Events / Year for Total Cumulative Flux)	Initial Meteor Mass (kg)	Fraction of Cumulative Flux	Number of Events per Year For Carbonaceous Meteors	Crater Radius (m) (for 15 km/sec)	Crater Diameter (km) (for 15 km/sec)	Crater Radius (m) (for 20 km/sec)	Crater Diameter (km) (for 20 km/sec)
3.16×10^{-08}	1.00×10^{15}	0.480	1.5×10^{-8}	210,000	420	300,000	600
1.00×10^{-07}	1.00×10^{14}	0.480	4.8×10^{-8}	100,000	200	130,000	260
1.00×10^{-06}	1.00×10^{13}	0.480	4.8×10^{-7}	43,000	86	70,000	140
3.16×10^{-06}	1.00×10^{12}	0.480	1.5×10^{-6}	20,000	40	28,000	56
1.00×10^{-05}	1.00×10^{11}	0.480	4.8×10^{-6}	1,000	2	1000	2
1.00×10^{-04}	1.00×10^{10}	0.480	4.8×10^{-5}	280	0.560	280	0.560
1.00×10^{-03}	1.00×10^{9}	0.480	4.8×10^{-4}	3	0.006	0.2	0.0004
1.00×10^{-02}	1.00×10^{8}	0.480	4.8×10^{-3}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
1.00×10^{-01}	1.00×10^{7}	0.945	9.5×10^{-2}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
1.00×10^{1}	1.00×10^{6}	0.925	9.3×10^{0}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
1.00×10^{2}	1.00×10^{5}	0.905	9.1×10^{1}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
6.31×10^{2}	1.00×10^{4}	0.885	5.6×10^{2}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
1.58×10^{3}	1.00×10^{3}	0.865	1.4×10^{3}	Shielding Effect	Shielding Effect	Shielding Effect	Shielding Effect
1.00×10^{4}	1.00×10^{2}	0.825	8.3×10^{3}	0.2	0.0004	Shielding Effect	Shielding Effect
1.58×10^{4}	1.00×10^{1}	0.785	1.2×10^{4}	0.1	0.0002	Shielding Effect	Shielding Effect
1.00×10^{5}	1.00×10^{0}	0.805	8.1×10^{4}	Off-scale	Off-scale	Off-scale	Off-scale
3.16×10^{5}	1.00×10^{-1}	0.805	2.5×10^{5}	Off-scale	Off-scale	Off-scale	Off-scale

Table IIB-8a. Cumulative Frequency of Cratering Impact Events by Crater Diameter (for $v_{initial}$ =15 km/sec)

Crater Diameter (km)	Number of Iron Meteorite Impacts (Curve 1)	Number of Iron Meteorite Impacts (Curve 2)	Number of Iron Meteorite Impacts (Curve 3)	Number of Stony Meteorite Impacts (Curve 1)	Number of Stony Meteorite Impacts (Curve 2)	Number of Carbonaceous Meteorite Impacts (Curve 1)	Number of Carbonaceous Meteorite Impacts (Curve 2)	Total Meteorite Impacts / Year	Frequency/km^2
.001	350			260				610	1.2×10^{-6}
.002	200			120	5.0×10^{-4}			320	6.2×10^{-7}
.005	75	1.0×10^{-2}		80	3.0×10^{-4}			155	3.0×10^{-7}
.007	60	1.0×10^{-1}	2.5×10^{-3}	70	2.7×10^{-4}		4.5×10^{-4}	130	2.5×10^{-7}
.009	50	2.7×10^{-1}	1.9×10^{-3}	60	2.2×10^{-4}		4.0×10^{-4}	110	2.1×10^{-7}
.01	45	3.5×10^{-1}	1.7×10^{-3}	60	2.1×10^{-4}		3.8×10^{-4}	105	2.0×10^{-7}
.02	30	9.0×10^{-1}	1.0×10^{-3}		1.7×10^{-4}		2.8×10^{-4}	31	6.0×10^{-8}
.03	20	1.1	5.0×10^{-4}		1.3×10^{-4}		2.1×10^{-4}	21	4.1×10^{-8}
.04	16	1.5	4.0×10^{-4}		1.2×10^{-4}		2.0×10^{-4}	18	3.5×10^{-8}
.05	11	1.7	3.8×10^{-4}		1.1×10^{-4}		1.8×10^{-4}	13	2.5×10^{-8}
.06	9	2.0	3.0×10^{-4}		1.0×10^{-4}		1.7×10^{-4}	11	2.1×10^{-8}
.07	7	2.7	2.8×10^{-4}		9.0×10^{-5}		1.5×10^{-4}	10	1.9×10^{-8}
.08	4		2.5×10^{-4}		8.5×10^{-5}		1.4×10^{-4}	4	7.7×10^{-9}
.09			2.3×10^{-4}		8.0×10^{-5}		1.3×10^{-4}	4.4×10^{-4}	8.5×10^{-13}
0.1			2.0×10^{-4}		7.0×10^{-5}		1.2×10^{-4}	3.9×10^{-4}	7.5×10^{-13}
0.2			9.0×10^{-5}		5.0×10^{-5}		9.0×10^{-5}	2.3×10^{-4}	4.4×10^{-13}
0.3			5.0×10^{-5}		3.7×10^{-5}		7.2×10^{-5}	1.6×10^{-4}	3.1×10^{-13}
0.4			3.5×10^{-5}		2.7×10^{-5}		6.0×10^{-5}	1.2×10^{-4}	2.3×10^{-13}
0.5			2.3×10^{-5}		2.0×10^{-5}		5.0×10^{-5}	9.3×10^{-5}	1.8×10^{-13}
0.6			2.0×10^{-5}		1.8×10^{-5}		4.5×10^{-5}	8.3×10^{-5}	1.6×10^{-13}
0.7			1.7×10^{-5}		1.5×10^{-5}		4.0×10^{-5}	7.2×10^{-5}	1.4×10^{-13}
0.8			1.3×10^{-5}		1.0×10^{-5}		3.0×10^{-5}	5.3×10^{-5}	1.0×10^{-13}
0.9			1.1×10^{-5}		9.0×10^{-6}		2.6×10^{-5}	4.6×10^{-5}	8.9×10^{-14}
1			1.0×10^{-5}		7.2×10^{-6}		2.0×10^{-5}	3.7×10^{-5}	7.2×10^{-14}
2			3.5×10^{-6}		3.7×10^{-6}		4.8×10^{-6}	1.2×10^{-5}	2.3×10^{-14}
3			2.0×10^{-6}		3.0×10^{-6}		3.8×10^{-6}	8.8×10^{-6}	1.7×10^{-14}
5			8.0×10^{-7}		2.1×10^{-6}		3.0×10^{-6}	5.9×10^{-6}	1.1×10^{-14}
10			3.0×10^{-7}		1.5×10^{-6}		2.5×10^{-6}	4.3×10^{-6}	8.3×10^{-15}

Table IIB-8b. Cumulative Frequency of Cratering Impact Events by Crater Diameter (for $v_{initial}$ =20 km/sec)

Crater Diameter (km)	Number of Iron Meteorite Impacts (Curve 1)	Number of Iron Meteorite Impacts (Curve 2)	Number of Iron Meteorite Impacts (Curve 3)	Number of Stony Meteorite Impacts (Curve 1)	Number of Stony Meteorite Impacts (Curve 2)	Number of Carbonaceous Meteorite Impacts (Curve 1)	Number of Carbonaceous Meteorite Impacts (Curve 2)	Total Meteorite Impacts / Year	Frequency/km^2
.001	200	5		100		3.5×10^{-4}		305	5.9×10^{-7}
.003	90	10	2.2×10^{-4}	70		2.8×10^{-4}		170	3.3×10^{-7}
.005	60	11	1.9×10^{-4}	55		2.3×10^{-4}		126	2.4×10^{-7}
.006	55	12	1.7×10^{-4}	50		2.1×10^{-4}		117	2.3×10^{-7}
.008	48	13	1.3×10^{-4}			2.0×10^{-4}		61	1.2×10^{-7}
.01	40	15	1.1×10^{-4}			1.8×10^{-4}		55	1.1×10^{-7}
.02	22	0	1.0×10^{-4}			1.6×10^{-4}		22	4.3×10^{-8}
.03			8.0×10^{-5}			1.5×10^{-4}		2.3×10^{-4}	4.4×10^{-13}
.04			7.0×10^{-5}			1.3×10^{-4}		2.0×10^{-4}	3.8×10^{-13}
.05			6.0×10^{-5}			1.2×10^{-4}		1.8×10^{-4}	3.5×10^{-13}
.06			5.5×10^{-5}			1.1×10^{-4}		1.6×10^{-4}	3.1×10^{-13}
.07			5.0×10^{-5}			1.0×10^{-4}		1.5×10^{-4}	2.9×10^{-13}
.08			4.5×10^{-5}	5.0×10^{-5}		1.0×10^{-4}		2.0×10^{-4}	3.9×10^{-13}
.09			4.0×10^{-5}	$4.5 \times 10 -^{5}$		9.5×10^{-5}		1.8×10^{-4}	3.5×10^{-13}
0.1			3.9×10^{-5}	4.0×10^{-5}		9.0×10^{-5}		1.7×10^{-4}	3.3×10^{-13}
0.2			2.0×10^{-5}	2.1×10^{-5}		7.5×10^{-5}		1.2×10^{-4}	2.3×10^{-13}
0.3			1.1×10^{-5}	1.7×10^{-5}		6.5×10^{-5}		9.3×10^{-5}	1.8×10^{-13}
0.4			8.0×10^{-6}	1.3×10^{-5}		6.0×10^{-5}		8.1×10^{-5}	1.6×10^{-13}
0.5			6.0×10^{-6}	1.0×10^{-5}		5.0×10^{-5}		6.6×10^{-5}	1.3×10^{-13}
0.6			5.0×10^{-6}	9.0×10^{-6}		4.5×10^{-5}		5.9×10^{-5}	1.1×10^{-13}
0.7			4.0×10^{-6}	8.0×10^{-6}		4.0×10^{-5}		5.2×10^{-5}	1.0×10^{-13}
0.8			3.5×10^{-6}	7.0×10^{-6}		3.5×10^{-5}		4.6×10^{-5}	8.9×10^{-14}
0.9			$3.0 \times 10 -^{6}$	6.5×10^{-6}		3.0×10^{-5}		4.0×10^{-5}	7.7×10^{-14}
1			2.5×10^{-6}	6.0×10^{-6}		2.2×10^{-5}		3.1×10^{-5}	6.0×10^{-14}
2			1.2×10^{-6}	4.0×10^{-6}		5.0×10^{-6}		1.0×10^{-5}	1.9×10^{-14}
3			8.0×10^{-7}	3.0×10^{-6}		4.0×10^{-6}		8.0×10^{-6}	1.5×10^{-14}
5			3.5×10^{-7}	2.0×10^{-6}		3.0×10^{-6}		5.0×10^{-6}	9.7×10^{-15}
10			2.0×10^{-7}	1.5×10^{-6}		2.6×10^{-6}		4.0×10^{-6}	7.7×10^{-15}

Table IIB-9a. Regression Analysis: $V_{initial}$ =15 km/sec, Upper Portion of Curve

Crater Diameter (km) (D)	Frequency/ km^2 (F) (for 15 km/sec)	Log D (x)	Log F (y)	Log D - Log D_{mean} $(x - x_{mean})$	$(\text{Log D - Log } D_{mean})^2$ $(x - x_{mean})^2$	Log F-Log F_{mean} $(y - y_{mean})$	(Log D - Log D_{mean}) x (Log F-Log F_{mean}) $(x - x_{mean})(y - y_{mean})$
0.001	1.2×10^{-06}	-3.00	-5.92×10^{00}	-1.18×10^{00}	1.40×10^{00}	1.14×10^{00}	-1.35×10^{00}
0.002	6.2×10^{-07}	-2.70	-6.21×10^{00}	-8.84×10^{-01}	7.81×10^{-01}	8.55×10^{-01}	-7.55×10^{-01}
0.005	3.0×10^{-07}	-2.30	-6.52×10^{00}	-4.86×10^{-01}	2.36×10^{-01}	5.39×10^{-01}	-2.62×10^{-01}
0.007	2.5×10^{-07}	-2.15	-6.60×10^{00}	-3.40×10^{-01}	1.16×10^{-01}	4.60×10^{-01}	-1.56×10^{-01}
0.009	2.1×10^{-07}	-2.05	-6.68×10^{00}	-2.31×10^{-01}	5.32×10^{-02}	3.85×10^{-01}	-8.87×10^{-02}
0.01	2.0×10^{-07}	-2.00	-6.70×10^{00}	-1.85×10^{-01}	3.42×10^{-02}	3.63×10^{-01}	-6.72×10^{-02}
0.02	6.0×10^{-08}	-1.70	-7.22×10^{00}	1.16×10^{-01}	1.35×10^{-02}	-1.60×10^{-01}	-1.85×10^{-02}
0.03	4.1×10^{-08}	-1.52	-7.39×10^{00}	2.92×10^{-01}	8.53×10^{-02}	-3.25×10^{-01}	-9.49×10^{-02}
0.04	3.5×10^{-08}	-1.40	-7.46×10^{00}	4.17×10^{-01}	1.74×10^{-01}	-3.94×10^{-01}	-1.64×10^{-01}
0.05	2.5×10^{-08}	-1.30	-7.60×10^{00}	5.14×10^{-01}	2.64×10^{-01}	-5.40×10^{-01}	-2.77×10^{-01}
0.06	2.1×10^{-08}	-1.22	-7.68×10^{00}	5.93×10^{-01}	3.52×10^{-01}	-6.15×10^{-01}	-3.65×10^{-01}
0.07	1.9×10^{-08}	-1.15	-7.72×10^{00}	6.60×10^{-01}	4.36×10^{-01}	-6.59×10^{-01}	-4.35×10^{-01}
0.08	7.7×10^{-09}	-1.10	-8.11×10^{00}	7.18×10^{-01}	5.16×10^{-01}	-1.05×10^{00}	-7.55×10^{-01}
Mean	- -	-1.82	-7.06	- -	- -	- -	- -
Sum	- -	- -	- -	- -	4.46×10^{00}	- -	-4.79×10^{00}
Slope	- -	-1.07	- -	- -	- -	- -	- -

Note:

$$\text{Slope} = \frac{\Sigma (x - x_{mean})(y - y_{mean})}{\Sigma (x - x_{mean})^2}$$

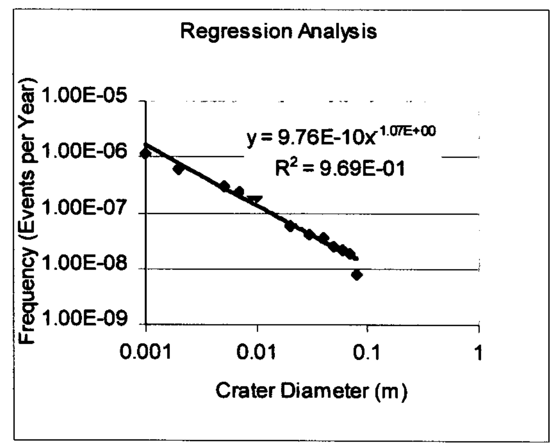

Table IIB-9b. Regression Analysis: $V_{initial}$ =15 km/sec, Lower Portion of Curve

Crater Diameter (km) (D)	Frequency/ km^2 (F) (for 15 km/sec)	Log D (x)	Log F (y)	Log D - Log D_{mean} $(x - x_{mean})$	(Log D - Log D_{mean})^2 $(x - x_{mean})^2$	Log F- Log F_{mean} $(y - y_{mean})$	(Log D - Log D_{mean}) x (Log F-Log F_{mean}) $(x - x_{mean})(y - y_{mean})$
0.09	8.5×10^{-13}	-1.05	-1.21×10^{01}	-9.12×10^{-01}	8.31×10^{-01}	9.29×10^{-01}	-8.47×10^{-01}
0.1	7.5×10^{-13}	-1.00	-1.21×10^{01}	-8.66×10^{-01}	7.50×10^{-01}	8.75×10^{-01}	-7.58E^{-01}
0.2	4.4×10^{-13}	-0.70	-1.24×10^{01}	-5.65×10^{-01}	3.19×10^{-01}	6.43×10^{-01}	-3.64×10^{-01}
0.3	3.1×10^{-13}	-0.52	-1.25×10^{01}	-3.89×10^{-01}	1.51×10^{-01}	4.91×10^{-01}	-1.91×10^{-01}
0.4	2.3×10^{-13}	-0.40	-1.26×10^{01}	-2.64×10^{-01}	6.97×10^{-02}	3.62×10^{-01}	-9.55×10^{-02}
0.5	1.8×10^{-13}	-0.30	-1.27×10^{01}	-1.67×10^{-01}	2.79×10^{-02}	2.55×10^{-01}	-4.27×10^{-02}
0.6	1.6×10^{-13}	-0.22	-1.28×10^{01}	-8.79×10^{-02}	7.73×10^{-03}	2.04×10^{-01}	-1.79×10^{-02}
0.7	1.4×10^{-13}	-0.15	-1.29×10^{01}	-2.10×10^{-02}	4.40×10^{-04}	1.46×10^{-01}	-3.07×10^{-03}
0.8	1.0×10^{-13}	-0.10	-1.30×10^{01}	3.70×10^{-02}	1.37×10^{-03}	0.00	0.00
0.9	8.9×10^{-14}	-0.05	-1.31×10^{01}	8.82×10^{-02}	7.77×10^{-03}	-5.06×10^{-02}	-4.46×10^{-03}
1	7.2×10^{-14}	0.00	-1.31×10^{01}	1.34×10^{-01}	1.79×10^{-02}	-1.43×10^{-01}	-1.91×10^{-02}
2	2.3×10^{-14}	0.30	-1.36×10^{01}	4.35×10^{-01}	1.89×10^{-01}	-6.38×10^{-01}	-2.78×10^{-01}
3	1.7×10^{-14}	0.48	-1.38×10^{01}	6.11×10^{-01}	3.73×10^{-01}	-7.70×10^{-01}	-4.70×10^{-01}
5	1.1×10^{-14}	0.70	-1.39×10^{01}	8.33×10^{-01}	6.94×10^{-01}	-9.59×10^{-01}	-7.98×10^{-01}
10	8.3×10^{-15}	1.00	-1.41×10^{01}	1.13 x 10 +00	1.29 x 10 +00	$-1.08 \times 10^{+00}$	$-1.23 \times 10^{+00}$
Mean	- -	-0.13	- -	- -	- -	- -	- -
Sum	- -	- -	- -	- -	4.73×10^{00}	- -	-5.10×10^{00}
Slope	- -	-1.08	- -	- -	- -	- -	- -

Note:

$$\text{Slope} = \frac{\Sigma\,(x - x_{mean})(y - y_{mean})}{\Sigma\,(x - x_{mean})^2}$$

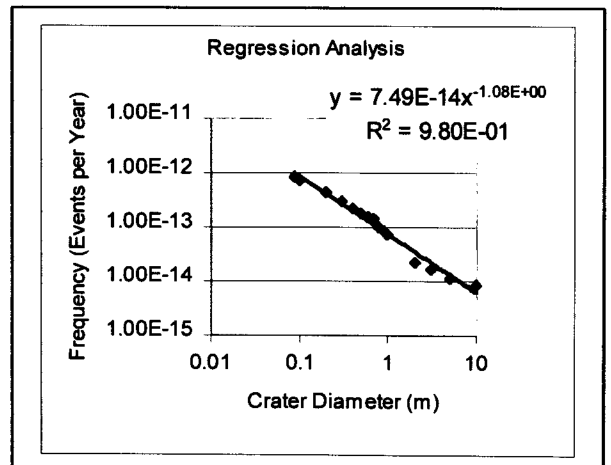

Table IIB-9c. Regression Analysis: $V_{initial}$ =20 km/sec, Upper Portion of Curve

Crater Diameter (km) (D)	Frequency/ km^2 (F) (for 20 km/sec)	Log D (x)	Log F (y)	Log D - Log D_{mean} $(x - x_{mean})$	(Log D - Log D_{mean} $)^2$ $(x - x_{mean})^2$	Log F- Log F_{mean} $(y - y_{mean})$	(Log D - Log D_{mean}) x (Log F-Log F_{mean}) $(x - x_{mean})(y - y_{mean})$
0.001	5.90×10^{-07}	-3.00	-6.23×10^{00}	-7.37×10^{-01}	5.43×10^{-01}	5.16×10^{-01}	-3.80×10^{-01}
0.003	3.30×10^{-07}	-2.52	-6.48×10^{00}	-2.60×10^{-01}	6.75×10^{-02}	2.63×10^{-01}	-6.84×10^{-02}
0.005	2.40×10^{-07}	-2.30	-6.62×10^{00}	-3.79×10^{-02}	1.44×10^{-03}	1.25×10^{-01}	-4.75×10^{-03}
0.006	2.30×10^{-07}	-2.22	-6.64×10^{00}	4.12×10^{-02}	1.70×10^{-03}	1.07×10^{-01}	4.40×10^{-03}
0.008	1.20×10^{-07}	-2.10	-6.92×10^{00}	1.66×10^{-01}	2.76×10^{-02}	-1.76×10^{-01}	-2.92×10^{-02}
0.01	1.10×10^{-07}	-2.00	-6.96×10^{00}	2.63×10^{-01}	6.92×10^{-02}	-2.14×10^{-01}	-5.62×10^{-02}
0.02	4.30×10^{-08}	-1.70	-7.37×10^{00}	5.64×10^{-01}	3.18×10^{-01}	-6.22×10^{-01}	-3.51×10^{-01}
Mean	- -	-2.26	- -	-6.74	- -	- -	- -
Sum	- -		- -	- -	1.03	- -	-0.88
Slope	- -	-0.86	- -	- -	- -	- -	- -

Note:

$$\text{Slope} = \frac{\Sigma (x - x_{mean})(y - y_{mean})}{\Sigma (x - x_{mean})^2}$$

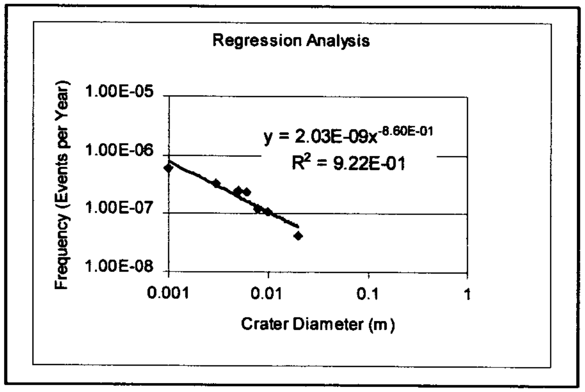

Table IIB-9d. Regression Analysis: $V_{initial}$ =20 km/sec, Lower Portion of Curve

Crater Diameter (km) (D)	Frequency/ km^2 (F) (for 20 km/sec)	Log D (x)	Log F (y)	Log D - Log D_{mean} ($x - x_{mean}$)	$(Log D - Log D_{mean})^2$ $(x - x_{mean})^2$	Log F- Log F_{mean} ($y - y_{mean}$)	(Log D - Log D_{mean}) x (Log F-Log F_{mean}) $(x - x_{mean})(y - y_{mean})$
0.03	4.40×10^{-13}	-1.52	-1.22×10^{01}	-1.06×10^{00}	1.13×10^{00}	5.82×10^{-01}	-6.17×10^{-01}
0.04	3.80×10^{-13}	-1.40	-1.23×10^{01}	-9.36×10^{-01}	8.76×10^{-01}	5.18×10^{-01}	-4.85×10^{-01}
0.05	3.50×10^{-13}	-1.30	-1.24×10^{01}	-8.39×10^{-01}	7.04×10^{-01}	4.82×10^{-01}	-4.05×10^{-01}
0.06	3.10×10^{-13}	-1.22	-1.24×10^{01}	-7.60×10^{-01}	5.77×10^{-01}	4.30×10^{-01}	-3.27×10^{-01}
0.07	2.90×10^{-13}	-1.15	-1.25×10^{01}	-6.93×10^{-01}	4.80×10^{-01}	4.01×10^{-01}	-2.78×10^{-01}
0.08	3.90×10^{-13}	-1.10	-1.24×10^{01}	-6.35×10^{-01}	4.03×10^{-01}	5.29×10^{-01}	-3.36×10^{-01}
0.09	3.50×10^{-13}	-1.05	-1.25×10^{01}	-5.84×10^{-01}	3.41×10^{-01}	4.82×10^{-01}	-2.82×10^{-01}
0.1	3.30×10^{-13}	-1.00	-1.25×10^{01}	-5.38×10^{-01}	2.89×10^{-01}	4.57×10^{-01}	-2.46×10^{-01}
0.2	2.30×10^{-13}	-0.70	-1.26×10^{01}	-2.37×10^{-01}	5.61×10^{-02}	3.00×10^{-01}	-7.11×10^{-02}
0.3	1.80×10^{-13}	-0.52	-1.27×10^{01}	-6.08×10^{-02}	3.69×10^{-03}	1.94×10^{-01}	-1.18×10^{-02}
0.4	1.60×10^{-13}	-0.40	-1.28×10^{01}	6.42×10^{-02}	4.12×10^{-03}	1.43×10^{-01}	9.15×10^{-03}
0.5	1.30×10^{-13}	-0.30	-1.29×10^{01}	1.61×10^{-01}	2.59×10^{-02}	5.24×10^{-02}	8.43×10^{-03}
0.6	1.10×10^{-13}	-0.22	-1.30×10^{01}	2.40×10^{-01}	5.77×10^{-02}	-2.02×10^{-02}	-4.85×10^{-03}
0.7	1.00×10^{-13}	-0.15	-1.30×10^{01}	3.07×10^{-01}	9.44×10^{-02}	-6.16×10^{-02}	-1.89×10^{-02}
0.8	8.90×10^{-14}	-0.10	-1.31×10^{01}	3.65×10^{-01}	1.33×10^{-01}	-1.12×10^{-01}	-4.10×10^{-02}
0.9	7.70×10^{-14}	-0.05	-1.31×10^{01}	4.16×10^{-01}	1.73×10^{-01}	-1.75×10^{-01}	-7.29×10^{-02}
1	6.00×10^{-14}	0.00	-1.32×10^{01}	4.62×10^{-01}	2.14×10^{-01}	-2.83×10^{-01}	-1.31×10^{-01}
2	1.90×10^{-14}	0.30	-1.37×10^{01}	7.63×10^{-01}	5.82×10^{-01}	-7.83×10^{-01}	-5.97×10^{-01}
3	1.50×10^{-14}	0.48	-1.38×10^{01}	9.39×10^{-01}	8.82×10^{-01}	-8.85×10^{-01}	-8.32×10^{-01}
5	9.70×10^{-15}	0.70	-1.40×10^{01}	1.16×10^{00}	1.35×10^{00}	$-1.07 \times 10^{+00}$	$-1.25 \times 10^{+00}$
10	7.70×10^{-15}	1.00	-1.41×10^{01}	1.46×10^{00}	2.14×10^{00}	$-1.18 \times 10^{+00}$	$-1.72 \times 10^{+00}$

Table IIB-9d. Regression Analysis: $V_{initial}$ =20 km/sec, Lower Portion of Curve (continued)

Crater Diameter (km) (D)	Frequency/ km^2 (F) (for 20 km/sec)	Log D (x)	Log F (y)	Log D - Log D_{mean} $(x - x_{mean})$	$(\text{Log D - Log } D_{mean})^2$ $(x - x_{mean})^2$	Log F- Log F_{mean} $(y - y_{mean})$	(Log D - Log D_{mean}) x (Log F-Log F_{mean}) $(x - x_{mean})(y - y_{mean})$
Mean	- -	-0.46	-12.92	- -	- -	- -	- -
Sum	- -	- -	- -	- -	1.05×10^{01}	- -	-7.70×10^{00}
Slope	- -	-0.73	- -	- -	- -	- -	- -

Note:

$$\text{Slope} = \frac{\Sigma (x- x_{mean})(y-y_{mean})}{\Sigma(x-x_{mean})^2}$$

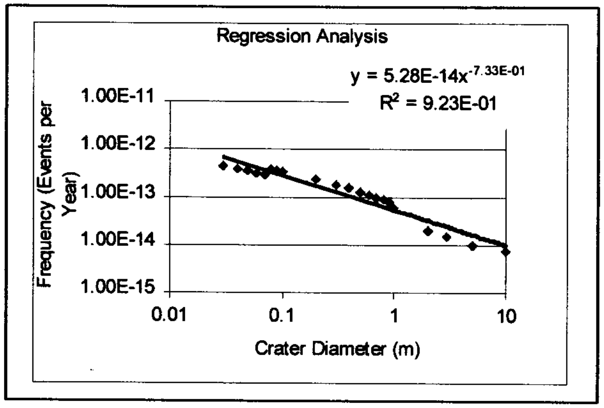

Table IIB-10a. Frequency (N) of Cratering Above Repository (v = 15 km/sec)

Repository Dimensions: Length (L) = 8.6 km Width (W) =1.3 km						
Upper Curve						
Crater Diameter	K (Table 9a)	k	k+1	k+2		N
(km)	9.76×10^{-10}	-1.07	-0.07	0.93	- -	– –
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	kK(Sum of Terms-F(D)$_{300}$)
0.001	9.76×10^{-10}	-1.7×10^{04}	-2.3×10^{02}	1.7×10^{-03}	-1.7×10^{04}	1.8×10^{-05}
0.002	9.76×10^{-10}	-8.1×10^{03}	-2.2×10^{02}	3.3×10^{-03}	-8.3×10^{03}	8.8×10^{-06}
0.005	9.76×10^{-10}	-3.0×10^{03}	-2.0×10^{02}	7.8×10^{-03}	-3.2×10^{03}	3.5×10^{-06}
0.007	9.76×10^{-10}	-2.1×10^{03}	-2.0×10^{02}	1.1×10^{-02}	-2.3×10^{03}	2.5×10^{-06}
0.009	9.76×10^{-10}	-1.6×10^{03}	-2.0×10^{02}	1.3×10^{-02}	-1.8×10^{03}	2.0×10^{-06}
0.01	9.76×10^{-10}	-1.4×10^{03}	-2.0×10^{02}	1.5×10^{-02}	-1.6×10^{03}	1.8×10^{-06}
0.02	9.76×10^{-10}	-6.9×10^{02}	-1.9×10^{02}	2.8×10^{-02}	-8.7×10^{02}	1.0×10^{-06}
0.03	9.76×10^{-10}	-4.5×10^{02}	-1.8×10^{02}	4.1×10^{-02}	-6.3×10^{02}	7.8×10^{-07}
0.04	9.76×10^{-10}	-3.3×10^{02}	-1.8×10^{02}	5.4×10^{-02}	-5.0×10^{02}	6.5×10^{-07}
0.05	9.76×10^{-10}	-2.6×10^{02}	-1.7×10^{02}	6.6×10^{-02}	-4.3×10^{02}	5.8×10^{-07}
0.06	9.76×10^{-10}	-2.1×10^{02}	-1.7×10^{02}	7.9×10^{-02}	-3.8×10^{02}	5.3×10^{-07}
0.07	9.76×10^{-10}	-1.8×10^{02}	-1.7×10^{02}	9.1×10^{-02}	-3.5×10^{02}	4.9×10^{-07}
0.08	9.76×10^{-10}	-1.6×10^{02}	-1.7×10^{02}	1.0×10^{-01}	-3.2×10^{02}	4.7×10^{-07}
300	9.76×10^{-10}	-2.3×10^{-02}	-9.5×10^{01}	2.2×10^{02}	1.2×10^{02}	0.0×10^{00}
Lower Curve						
Crater Diameter	K (Table 9b)	k	k+1	k+2	- -	N
(km)	7.49×10^{-14}	-1.08	-0.08	0.92	- -	– –
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	kK(Sum of Terms-F(D)$_{300}$)
0.09	7.49×10^{-14}	-1.4×10^{02}	-1.5×10^{02}	1.2×10^{-01}	-2.9×10^{02}	3.4×10^{-11}
0.1	7.49×10^{-14}	-1.2×10^{02}	-1.5×10^{02}	1.3×10^{-01}	-2.7×10^{02}	3.2×10^{-11}
0.2	7.49×10^{-14}	-5.9×10^{01}	-1.4×10^{02}	2.5×10^{-01}	-2.0×10^{02}	2.6×10^{-11}
0.3	7.49×10^{-14}	-3.8×10^{01}	-1.4×10^{02}	3.6×10^{-01}	-1.7×10^{02}	2.4×10^{-11}
0.4	7.49×10^{-14}	-2.8×10^{01}	-1.3×10^{02}	4.7×10^{-01}	-1.6×10^{02}	2.3×10^{-11}
0.5	7.49×10^{-14}	-2.2×10^{01}	-1.3×10^{02}	5.7×10^{-01}	-1.5×10^{02}	2.3×10^{-11}
0.6	7.49×10^{-14}	-1.8×10^{01}	-1.3×10^{02}	6.8×10^{-01}	-1.5×10^{02}	2.2×10^{-11}
0.7	7.49×10^{-14}	-1.5×10^{01}	-1.3×10^{02}	7.8×10^{-01}	-1.4×10^{02}	2.2×10^{-11}
0.8	7.49×10^{-14}	-1.3×10^{01}	-1.3×10^{02}	8.9×10^{-01}	-1.4×10^{02}	2.2×10^{-11}
0.9	7.49×10^{-14}	-1.2×10^{01}	-1.2×10^{02}	9.9×10^{-01}	-1.4×10^{02}	2.1×10^{-11}
1	7.49×10^{-14}	-1.0×10^{01}	-1.2×10^{02}	1.1×10^{00}	-1.3×10^{02}	2.1×10^{-11}
2	7.49×10^{-14}	-4.9×10^{00}	-1.2×10^{02}	2.1×10^{00}	-1.2×10^{02}	2.0×10^{-11}
3	7.49×10^{-14}	-3.2×10^{00}	-1.1×10^{02}	3.0×10^{00}	-1.1×10^{02}	2.0×10^{-11}
5	7.49×10^{-14}	-1.8×10^{00}	-1.1×10^{02}	4.8×10^{00}	-1.1×10^{02}	1.9×10^{-11}
10	7.49×10^{-14}	-8.6×10^{-01}	-1.0×10^{02}	9.0×10^{00}	-9.5×10^{01}	1.8×10^{-11}
300	7.49×10^{-14}	-2.2×10^{-02}	-7.8×10^{01}	2.1×10^{02}	1.3×10^{02}	0.0×10^{00}

$$N = k\,K\left[\frac{LW(D)^{k}}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right]_{D}^{300}$$

Where

N	= frequency of impacts capable of disrupting the repository		L	=	length of the repository
K	= the proportionality constant (from regression analysis)		W	=	width of the repository
k	= power of the distribution (from regression analysis)		D	=	diameter of the crater

Table IIB-10b. Frequency (N) of Cratering Above Repository (v = 20 km/sec)

Repository Dimensions: Length (L) = 8.6 km Width (W) =1.3 km						
Upper Curve						
Crater Diameter	K (Table 9c)	k	k+1	k+2	- -	N
(km)	2.03×10^{-09}	-0.86	0.14	1.14	- -	– –
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	kK(Sum of Terms-F(D)$_{300}$)
0.001	2.03×10^{-0}	-4.9×10^{03}	2.7×10^{01}	3.3×10^{-04}	-4.9×10^{03}	9.9×10^{-06}
0.003	2.03×10^{-0}	-1.9×10^{03}	3.1×10^{01}	1.2×10^{-03}	-1.9×10^{03}	4.6×10^{-06}
0.005	2.03×10^{-0}	-1.2×10^{03}	3.4×10^{01}	2.1×10^{-03}	-1.2×10^{03}	3.4×10^{-06}
0.006	2.03×10^{-0}	-1.1×10^{03}	3.5×10^{01}	2.6×10^{-03}	-1.0×10^{03}	3.1×10^{-06}
0.008	2.03×10^{-0}	-8.3×10^{02}	3.6×10^{01}	3.6×10^{-03}	-7.9×10^{02}	2.7×10^{-06}
0.01	2.03×10^{-0}	-6.8×10^{02}	3.7×10^{01}	4.6×10^{-03}	-6.5×10^{02}	2.4×10^{-06}
0.02	2.03×10^{-0}	-3.8×10^{02}	4.1×10^{01}	1.0×10^{-02}	-3.3×10^{02}	1.9×10^{-06}
300	2.03×10^{-0}	-9.6×10^{-02}	1.6×10^{02}	5.8×10^{02}	7.4×10^{02}	0.0×10^{00}
Lower Curve						
Crater Diameter	K (Table 9d)	k	k+1	k+2	- -	N
(km)	5.28×10^{-14}	-0.73	0.27	1.27	- -	– –
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	kK(Sum of Terms-F(D)$_{300}$)
0.03	5.28×10^{-1}	-2.0×10^{02}	1.4×10^{01}	9.2×10^{-03}	-1.8×10^{02}	5.6×10^{-11}
0.04	5.28×10^{-1}	-1.6×10^{02}	1.5×10^{01}	1.3×10^{-02}	-1.5×10^{02}	5.5×10^{-11}
0.05	5.28×10^{-1}	-1.4×10^{02}	1.6×10^{01}	1.8×10^{-02}	-1.2×10^{02}	5.4×10^{-11}
0.06	5.28×10^{-1}	-1.2×10^{02}	1.7×10^{01}	2.2×10^{-02}	-1.0×10^{02}	5.3×10^{-11}
0.07	5.28×10^{-1}	-1.1×10^{02}	1.8×10^{01}	2.7×10^{-02}	-8.9×10^{01}	5.2×10^{-11}
0.08	5.28×10^{-1}	-9.7×10^{01}	1.9×10^{01}	3.2×10^{-02}	-7.8×10^{01}	5.2×10^{-11}
0.09	5.28×10^{-1}	-8.9×10^{01}	1.9×10^{01}	3.7×10^{-02}	-7.0×10^{01}	5.2×10^{-11}
0.1	5.28×10^{-1}	-8.2×10^{01}	2.0×10^{01}	4.2×10^{-02}	-6.3×10^{01}	5.1×10^{-11}
0.2	5.28×10^{-1}	-5.0×10^{01}	2.4×10^{01}	1.0×10^{-01}	-2.6×10^{01}	5.0×10^{-11}
0.3	5.28×10^{-1}	-3.7×10^{01}	2.6×10^{01}	1.7×10^{-01}	-1.0×10^{01}	4.9×10^{-11}
0.4	5.28×10^{-1}	-3.0×10^{01}	2.9×10^{01}	2.5×10^{-01}	-1.0×10^{00}	4.9×10^{-11}
0.5	5.28×10^{-1}	-2.5×10^{01}	3.0×10^{01}	3.3×10^{-01}	5.3×10^{00}	4.9×10^{-11}
0.6	5.28×10^{-1}	-2.2×10^{01}	3.2×10^{01}	4.1×10^{-01}	1.0×10^{01}	4.9×10^{-11}
0.7	5.28×10^{-1}	-2.0×10^{01}	3.3×10^{01}	5.0×10^{-01}	1.4×10^{01}	4.9×10^{-11}
0.8	5.28×10^{-1}	-1.8×10^{01}	3.5×10^{01}	5.9×10^{-01}	1.7×10^{01}	4.8×10^{-11}
0.9	5.28×10^{-1}	-1.7×10^{01}	3.6×10^{01}	6.9×10^{-01}	2.0×10^{01}	4.8×10^{-11}
1	5.28×10^{-1}	-1.5×10^{01}	3.7×10^{01}	7.9×10^{-01}	2.2×10^{01}	4.8×10^{-11}
2	5.28×10^{-1}	-9.2×10^{00}	4.4×10^{01}	1.9×10^{00}	3.7×10^{01}	4.8×10^{-11}
3	5.28×10^{-1}	-6.9×10^{00}	4.9×10^{01}	3.2×10^{00}	4.6×10^{01}	4.7×10^{-11}
5	5.28×10^{-1}	-4.7×10^{00}	5.7×10^{01}	6.1×10^{00}	5.8×10^{01}	4.7×10^{-11}
10	5.28×10^{-1}	-2.9×10^{00}	6.8×10^{01}	1.5×10^{01}	8.0×10^{01}	4.6×10^{-11}
300	5.28×10^{-1}	-2.4×10^{-01}	1.7×10^{02}	1.1×10^{03}	1.3×10^{03}	0.0×10^{00}

$$N = k\,K\left[\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right]_D^{300}$$

Where

N	=	frequency of impacts capable of disrupting the repository	L	=	length of the repository
K	=	the proportionality constant (from regression analysis)	W	=	width of the repository
k	=	power of the distribution (from regression analysis)	D	=	diameter of the crater

Table IIB-10c. Frequency (N) of Cratering Above Repository (After Grieve)

Repository Dimensions: Length (L) = 8.6 km Width (W) =1.3 km						
Crater Diameter	K (from Grieve, 1987)	k	k+1	k+2		N
(km)	1.20×10^{-12}	-1.80	-0.80	0.20	- -	– –
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	kK(Sum of Terms-F(D)300)
0.001	1.20×10^{-12}	-1.6×10^{06}	-3.1×10^{03}	1.3×10^{00}	-1.6×10^{06}	3.4×10^{-06}
0.01	1.20×10^{-12}	-2.5×10^{04}	-4.9×10^{02}	2.0×10^{00}	-2.5×10^{04}	5.5×10^{-08}
0.1	1.20×10^{-12}	-3.9×10^{02}	-7.8×10^{01}	3.2×10^{00}	-4.7×10^{02}	1.0×10^{-09}
1	1.20×10^{-12}	-6.2×10^{00}	-1.2×10^{01}	5.0×10^{00}	-1.4×10^{01}	6.3×10^{-11}
10	1.20×10^{-12}	-9.8×10^{-02}	-2.0×10^{00}	7.9×10^{00}	5.9×10^{00}	2.1×10^{-11}
100	1.20×10^{-12}	-1.6×10^{-03}	-3.1×10^{-01}	1.3×10^{01}	1.2×10^{01}	7.1×10^{-12}
300	1.20×10^{-12}	-2.2×10^{-04}	-1.3×10^{-01}	1.6×10^{01}	1.6×10^{01}	0.0×10^{00}

$$N = k\,K\left[\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right]_D^{300}$$

Where

N = frequency of impacts capable of disrupting the repository

K = the proportionality constant (from regression analysis)

k = power of the distribution (from regression analysis)

L = length of the repository

W = width of the repository

D = diameter of the crater

Table IIB-11a. Frequency (N) of Cratering Above Outcrop (v = 15 km/sec)

Outcrop Dimensions: Length (L) = 1.1 km Width (W) =0.1km						
Upper Curve						
Crater Diameter	K (Table 9a)	k	k+1	k+2	- -	N
(km)	9.76×10^{-10}	-1.07	-0.07	0.93	- -	_ _
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	kK(Sum of Terms-F(D)300)
0.001	9.76×10^{-10}	-1.7×10^{02}	-2.8×10^{01}	1.7×10^{-03}	-1.9×10^{02}	4.2×10^{-07}
0.002	9.76×10^{-10}	-7.9×10^{01}	-2.6×10^{01}	3.3×10^{-03}	-1.1×10^{02}	3.2×10^{-07}
0.005	9.76×10^{-10}	-3.0×10^{01}	-2.5×10^{01}	7.8×10^{-03}	-5.5×10^{01}	2.7×10^{-07}
0.007	9.76×10^{-10}	-2.1×10^{01}	-2.4×10^{01}	1.1×10^{-02}	-4.5×10^{01}	2.6×10^{-07}
0.009	9.76×10^{-10}	-1.6×10^{01}	-2.4×10^{01}	1.3×10^{-02}	-4.0×10^{01}	2.6×10^{-07}
0.01	9.76×10^{-10}	-1.4×10^{01}	-2.4×10^{01}	1.5×10^{-02}	-3.8×10^{01}	2.5×10^{-07}
0.02	9.76×10^{-10}	-6.8×10^{00}	-2.3×10^{01}	2.8×10^{-02}	-2.9×10^{01}	2.4×10^{-07}
0.03	9.76×10^{-10}	-4.4×10^{00}	-2.2×10^{01}	4.1×10^{-02}	-2.6×10^{01}	2.4×10^{-07}
0.04	9.76×10^{-10}	-3.2×10^{00}	-2.1×10^{01}	5.4×10^{-02}	-2.5×10^{01}	2.4×10^{-07}
0.05	9.76×10^{-10}	-2.5×10^{00}	-2.1×10^{01}	6.6×10^{-02}	-2.4×10^{01}	2.4×10^{-07}
0.06	9.76×10^{-10}	-2.1×10^{00}	-2.1×10^{01}	7.9×10^{-02}	-2.3×10^{01}	2.4×10^{-07}
0.07	9.76×10^{-10}	-1.8×10^{00}	-2.1×10^{01}	9.1×10^{-02}	-2.2×10^{01}	2.4×10^{-07}
0.08	9.76×10^{-10}	-1.5×10^{00}	-2.0×10^{01}	1.0×10^{-01}	-2.2×10^{01}	2.4×10^{-07}
300	9.76×10^{-10}	-2.3×10^{-04}	-1.1×10^{01}	2.2×10^{02}	2.0×10^{02}	0.0×10^{00}
Lower Curve						
Crater Diameter	K (Table 9b)	k	k+1	k+2	- -	N
(km)	7.49×10^{-14}	-1.08	-0.08	0.92	- -	_ _
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	kK(Sum of Terms-F(D)300)
0.09	7.49×10^{-14}	-1.4×10^{00}	-1.8×10^{01}	1.2×10^{-01}	-1.9×10^{01}	1.8×10^{-11}
0.1	7.49×10^{-14}	-1.2×10^{00}	-1.8×10^{01}	1.3×10^{-01}	-1.9×10^{01}	1.7×10^{-11}
0.2	7.49×10^{-14}	-5.8×10^{-01}	-1.7×10^{01}	2.5×10^{-01}	-1.7×10^{01}	1.7×10^{-11}
0.3	7.49×10^{-14}	-3.7×10^{-01}	-1.7×10^{01}	3.6×10^{-01}	-1.7×10^{01}	1.7×10^{-11}
0.4	7.49×10^{-14}	-2.7×10^{-01}	-1.6×10^{01}	4.7×10^{-01}	-1.6×10^{01}	1.7×10^{-11}
0.5	7.49×10^{-14}	-2.2×10^{-01}	-1.6×10^{01}	5.7×10^{-01}	-1.5×10^{01}	1.7×10^{-11}
0.6	7.49×10^{-14}	-1.8×10^{-01}	-1.6×10^{01}	6.8×10^{-01}	-1.5×10^{01}	1.7×10^{-11}
0.7	7.49×10^{-14}	-1.5×10^{-01}	-1.5×10^{01}	7.8×10^{-01}	-1.5×10^{01}	1.7×10^{-11}
0.8	7.49×10^{-14}	-1.3×10^{-01}	-1.5×10^{01}	8.9×10^{-01}	-1.5×10^{01}	1.7×10^{-11}
0.9	7.49×10^{-14}	-1.1×10^{-01}	-1.5×10^{01}	9.9×10^{-01}	-1.4×10^{01}	1.7×10^{-11}
1	7.49×10^{-14}	-1.0×10^{-01}	-1.5×10^{01}	1.1×10^{00}	-1.4×10^{01}	1.7×10^{-11}
2	7.49×10^{-14}	-4.8×10^{-02}	-1.4×10^{01}	2.1×10^{00}	-1.2×10^{01}	1.7×10^{-11}
3	7.49×10^{-14}	-3.1×10^{-02}	-1.4×10^{01}	3.0×10^{00}	-1.1×10^{01}	1.7×10^{-11}
5	7.49×10^{-14}	-1.8×10^{-02}	-1.3×10^{01}	4.8×10^{00}	-8.4×10^{00}	1.7×10^{-11}
10	7.49×10^{-14}	-8.5×10^{-03}	-1.2×10^{01}	9.0×10^{00}	-3.4×10^{00}	1.6×10^{-11}
300	7.49×10^{-14}	-2.2×10^{-04}	-9.5×10^{00}	2.1×10^{02}	2.0×10^{02}	0.0×10^{00}

$$N = k\,K \left[\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right]_D^{300}$$

Where

N	=	frequency of impacts capable of disrupting the repository	L	=	length of the repository
K	=	the proportionality constant (from regression analysis)	W	=	width of the repository
k	=	power of the distribution (from regression analysis)	D	=	diameter of the crater

Table IIB-11b. Frequency (N) of Cratering Above Outcrop (v = 20 km/sec)

Outcrop Dimensions: Length (L) = 1.1 km Width (W) = 0.1km						
			Upper Curve			
Crater Diameter (km)	K (Table 9c) 2.03×10^{-09}	k -0.86	k+1 0.14	k+2 1.14	- -	N —
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	$kK(\text{Sum of Terms-F(D)}_{300})$
0.001	2.03×10^{-09}	-4.9×10^{01}	3.3×10^{00}	3.3×10^{-04}	-4.5×10^{01}	1.1×10^{-06}
0.002	2.03×10^{-09}	-2.7×10^{01}	3.6×10^{00}	7.3×10^{-04}	-2.3×10^{01}	1.1×10^{-06}
0.005	2.03×10^{-09}	-1.2×10^{01}	4.1×10^{00}	2.1×10^{-03}	-8.1×10^{00}	1.1×10^{-06}
0.007	2.03×10^{-09}	-9.1×10^{00}	4.3×10^{00}	3.1×10^{-03}	-4.8×10^{00}	1.1×10^{-06}
0.009	2.03×10^{-09}	-7.3×10^{00}	4.4×10^{00}	4.1×10^{-03}	-2.9×10^{00}	1.1×10^{-06}
0.01	2.03×10^{-09}	-6.7×10^{00}	4.5×10^{00}	4.6×10^{-03}	-2.2×10^{00}	1.1×10^{-06}
0.02	2.03×10^{-09}	-3.7×10^{00}	5.0×10^{00}	1.0×10^{-02}	1.3×10^{00}	1.1×10^{-06}
300	2.03×10^{-09}	-9.5×10^{-04}	1.9×10^{01}	5.8×10^{02}	6.0×10^{02}	0.0×10^{00}
			Lower Curve			
Crater Diameter (km)	K (Table 9d) 5.28×10^{-14}	k -0.73	k+1 0.27	k+2 1.27	- -	N —
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	$kK(\text{Sum of Terms-F(D)}_{300})$
0.03	5.28×10^{-14}	-1.9×10^{00}	1.7×10^{00}	9.2×10^{-03}	-2.2×10^{-01}	4.3×10^{-11}
0.04	5.28×10^{-14}	-1.6×10^{00}	1.9×10^{00}	1.3×10^{-02}	3.0×10^{-01}	4.3×10^{-11}
0.05	5.28×10^{-14}	-1.3×10^{00}	2.0×10^{00}	1.8×10^{-02}	6.5×10^{-01}	4.3×10^{-11}
0.06	5.28×10^{-14}	-1.2×10^{00}	2.1×10^{00}	2.2×10^{-02}	9.3×10^{-01}	4.3×10^{-11}
0.07	5.28×10^{-14}	-1.0×10^{00}	2.2×10^{00}	2.7×10^{-02}	1.1×10^{00}	4.3×10^{-11}
0.08	5.28×10^{-14}	-9.5×10^{-01}	2.2×10^{00}	3.2×10^{-02}	1.3×10^{00}	4.3×10^{-11}
0.09	5.28×10^{-14}	-8.7×10^{-01}	2.3×10^{00}	3.7×10^{-02}	1.5×10^{00}	4.3×10^{-11}
0.1	5.28×10^{-14}	-8.1×10^{-01}	2.4×10^{00}	4.2×10^{-02}	1.6×10^{00}	4.3×10^{-11}
0.2	5.28×10^{-14}	-4.9×10^{-01}	2.9×10^{00}	1.0×10^{-01}	2.5×10^{00}	4.3×10^{-11}
0.3	5.28×10^{-14}	-3.6×10^{-01}	3.2×10^{00}	1.7×10^{-01}	3.0×10^{00}	4.3×10^{-11}
0.4	5.28×10^{-14}	-2.9×10^{-01}	3.5×10^{00}	2.5×10^{-01}	3.4×10^{00}	4.3×10^{-11}
0.5	5.28×10^{-14}	-2.5×10^{-01}	3.7×10^{00}	3.3×10^{-01}	3.8×10^{00}	4.3×10^{-11}
0.6	5.28×10^{-14}	-2.2×10^{-01}	3.9×10^{00}	4.1×10^{-01}	4.1×10^{00}	4.3×10^{-11}
0.7	5.28×10^{-14}	-2.0×10^{-01}	4.0×10^{00}	5.0×10^{-01}	4.3×10^{00}	4.3×10^{-11}
0.8	5.28×10^{-14}	-1.8×10^{-01}	4.2×10^{00}	5.9×10^{-01}	4.6×10^{00}	4.3×10^{-11}
0.9	5.28×10^{-14}	-1.6×10^{-01}	4.3×10^{00}	6.9×10^{-01}	4.8×10^{00}	4.3×10^{-11}
1	5.28×10^{-14}	-1.5×10^{-01}	4.4×10^{00}	7.9×10^{-01}	5.1×10^{00}	4.3×10^{-11}
2	5.28×10^{-14}	-9.1×10^{-02}	5.4×10^{00}	1.9×10^{00}	7.2×10^{00}	4.3×10^{-11}
3	5.28×10^{-14}	-6.8×10^{-02}	6.0×10^{00}	3.2×10^{00}	9.1×10^{00}	4.3×10^{-11}
5	5.28×10^{-14}	-4.7×10^{-02}	6.9×10^{00}	6.1×10^{00}	1.3×10^{01}	4.3×10^{-11}
10	5.28×10^{-14}	-2.8×10^{-02}	8.3×10^{00}	1.5×10^{01}	2.3×10^{01}	4.2×10^{-11}
300	5.28×10^{-14}	-2.3×10^{-03}	2.1×10^{01}	1.1×10^{03}	1.1×10^{03}	0.0×10^{00}

$$N = k\,K\left[\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right]_D^{300}$$

Where

N = frequency of impacts capable of disrupting the repository
K = the proportionality constant (from regression analysis)
k = power of the distribution (from regression analysis)
L = length of the repository
W = width of the repository
D = diameter of the crater

Table IIB-11c. Frequency (N) of Cratering Above Outcrop (After Grieve, 1987)

Outcrop Dimensions: Length (L) = 1.1 km Width (W) =1.0 km						
Crater Diameter	K (from Grieve 1987)	k	k+1	k+2	- -	N
(km)	1.20×10^{-12}	-1.80	-0.80	0.20	- -	— —
D	K	LWD^k/k	$(L+W)(D^{k+1})/k+1$	$D^{k+2}/k+2$	Sum of Terms	$kK(\text{Sum of Terms}-F(D)_{300})$
0.001	1.20×10^{-12}	-1.5×10^{04}	-3.8×10^{02}	1.3×10^{00}	-1.6×10^{04}	3.4×10^{-08}
0.01	1.20×10^{-12}	-2.4×10^{02}	-6.0×10^{01}	2.0×10^{00}	-3.0×10^{02}	6.8×10^{-10}
0.1	1.20×10^{-12}	-3.9×10^{00}	-9.5×10^{00}	3.2×10^{00}	-1.0×10^{01}	5.6×10^{-11}
1	1.20×10^{-12}	-6.1×10^{-02}	-1.5×10^{00}	5.0×10^{00}	3.4×10^{00}	2.6×10^{-11}
10	1.20×10^{-12}	-9.7×10^{-04}	-2.4×10^{-01}	7.9×10^{00}	7.7×10^{00}	1.7×10^{-11}
100	1.20×10^{-12}	-1.5×10^{-05}	-3.8×10^{-02}	1.3×10^{01}	1.3×10^{01}	6.7×10^{-12}
300	1.20×10^{-12}	-2.1×10^{-06}	-1.6×10^{-02}	1.6×10^{01}	1.6×10^{01}	0.0×10^{00}

$$N = k\,K\left[\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right]_D^{300}$$

Where

N	=	frequency of impacts capable of disrupting the repository	L	=	length of the repository
K	=	the proportionality constant (from regression analysis)	W	=	width of the repository
k	=	power of the distribution (from regression analysis)	D	=	diameter of the crate

ATTACHMENT III

CRITICALITY FEPs
PRIMARY AND SECONDARY FEP DESCRIPTIONS

Primary: Criticality in Waste and EBS

FEP Number (2.1.14.01.00)	**Primary Description:** Nuclear criticality refers to a sustained fission reaction that requires a sufficient concentration and localized (critical) mass of fissile isotopes (e.g., U-235, Pu-239). [Thermal criticality requires the additional] presence of neutron moderating materials (e.g., water) in a suitable geometry. [Fast criticality can occur without moderator, but generally requires a much larger critical mass than thermal criticality. Criticality can be prevented by the presence of neutron absorbing elements (e.g., boron, gadolinium)]. Within the waste and EBS, a critical mass may occur within the waste package (in-situ) or out of the waste package and in the drift (near-field). This FEP aggregates all mechanisms for in-situ and near-field criticality into a single category. Specific processes that could produce criticality are discussed in FEPs (2.1.14.03.00) through (2.1.14.08.00) (for in-situ) and in FEPs (2.1.14.09.00) through (2.1.14.14.00) (for out-of-container)].	
Primary Assigned to: *Criticalityl FEPs*		
Screening Decision: *Excluded* from the TSPA–SR (Preliminary	**Screening Decision Basis**: Low probability	
Number of Secondaries: 17		

Primary: **Criticality in waste and EBS**
Secondary: Criticality (in waste and EBS)

FEP Number (2.1.14.01.01)	**Originator FEP Description**: Critical masses of 235U or 238Pu or both could be accumulated in the vault resulting in fission reactions. (AECL)

Primary: **Criticality in waste and EBS**
Secondary: Criticality (in waste and EBS)

FEP Number (2.1.14.01.02)	**Originator FEP Description**: Critical masses of 235U or 238Pu or both could be accumulated in the vault resulting in fission reactions. (AECL)

Primary: **Criticality in waste and EBS**
Secondary: Nuclear Criticality (in waste and EBS)

FEP Number (2.1.14.01.03)	**Originator FEP Description**: (none) (NEA)

Primary: **Criticality in waste and EBS**
Secondary: Nuclear Criticality (in waste and EBS)

FEP Number (2.1.14.01.04)	**Originator FEP Description**: A detailed analysis of the potential for criticality in CANDU spent fuel has been carried out by McCamus (1992). This showed that criticality could not occur whether the used fuel remained intact or was uniformly distributed in the container. For criticality to occur outside the waste container, segregation and accumulation of one or more fissile materials would be required. etc. (NAGRA)

Primary: **Criticality in waste and EBS**
Secondary: Nuclear Criticality (in waste and EBS)

FEP Number (2.1.14.01.05)	**Originator FEP Description**: The accumulation of a sufficient mass of fissile material such that a self-sustaining nuclear fission reaction can occur. Such a process would generate heat and quantities of fission products and actinide elements which would not other wise be accounted for in low and intermediate-level wastes. [They recommend that criticality be omitted from all assessments] (UK-HMIP)

Primary: **Criticality in waste and EBS**
Secondary: Nuclear Criticality: heat (in waste and EBS)

FEP Number (2.1.14.01.06)	**Originator FEP Description**: Nuclear criticality refers to a sustained fission reaction that may occur if fissile radionuclides reach both a sufficiently high concentration and total mass (where the latter parameter includes the influence of enrichment of the fissile radionuclides). ... The possibility of a nuclear criticality in the WIPP waste disposal region has been eliminated from performance assessment calculations because of the low initial concentration of the fissile radionuclides ... and because no credible mechanism exists to further concentrate the fissile radionuclides after closure. (WIPP)

Primary: **Criticality in waste and EBS**
Secondary: Nuclear explosions (in waste and EBS)

FEP Number (2.1.14.01.07)	**Originator FEP Description**: For a nuclear explosion to occur, a critical mass of plutonium would have to undergo rapid compression to a high density. Even if a critical mass of plutonium could form in the system, there is no mechanism for rapid compression. etc. (WIPP)

Primary: **Criticality in waste and EBS**
Secondary: DOE SNF criticality in-situ

FEP Number (2.1.14.01.08)	**Originator FEP Description**: The DOE SNF to be disposed of in Yucca Mountain might have the potential to result in a criticality within the waste package. The potential for criticality for DOE SNF may differ from that for commercial SNF.

Primary: **Criticality in waste and EBS**
Secondary: DOE SNF criticality in-situ (radionuclide inventory impact)

FEP Number (2.1.14.01.09)	**Originator FEP Description**: The DOE SNF to be disposed of in Yucca Mountain might have the potential to result in a criticality within the waste package. A criticality event could increase the radionuclide inventory available for transport to the groundwater.

Primary: **Criticality in waste and EBS**
Secondary: DOE SNF criticality near-field (radionuclide inventory impact)

FEP Number (2.1.14.01.10)	**Originator FEP Description**: The DOE SNF to be disposed of in Yucca Mountain might have the potential to result in a criticality within the near-field region, if selective transport of fissile material occurs and other conditions are met. A criticality event could increase the radionuclide inventory available for transport to the groundwater.

Primary: **Criticality in waste and EBS**
Secondary: DOE SNF criticality in-situ (waste heat impact)

FEP Number (2.1.14.01.11)	**Originator FEP Description**: The DOE SNF to be disposed of in Yucca Mountain might have the potential to result in a criticality within the waste package. A criticality event could increase the waste heat generation during the event, thereby affecting thermal hydrology and seepage onto the waste packages.

Primary: **Criticality in waste and EBS**
Secondary: DOE SNF criticality in-situ (waste package degradation impact)

FEP Number (2.1.14.01.12)	**Originator FEP Description**: The DOE SNF to be disposed of in Yucca Mountain might have the potential to result in a criticality within the waste package. A criticality event may have an adverse impact on waste package degradation.

Primary: **Criticality in waste and EBS**
Secondary: DOE SNF criticality in-situ (waste form degradation impact)

FEP Number (2.1.14.01.13)	**Originator FEP Description**: The DOE SNF to be disposed of in Yucca Mountain might have the potential to result in a criticality within the waste package. A criticality event might impact fuel degradation.

Primary: **Criticality in waste and EBS**
Secondary: DOE SNF criticality in-situ (cladding degradation impact)

FEP Number (2.1.14.01.14)	**Originator FEP Description**: The DOE SNF to be disposed of in Yucca Mountain might have the potential to result in a criticality within the waste package. A criticality event may impact the DOE SNF cladding degradation.

Primary: **Criticality in waste and EBS**
Secondary: Differential solubility of neutron poisons

FEP Number (2.1.14.01.15)	**Originator FEP Description**: The solubility of the neutron poisons differs from the solubility of the fissile radionuclides (YMP)

Primary: **Criticality in waste and EBS**
Secondary: Selective leaching of fissile materials

FEP Number (2.1.14.01.16	**Originator FEP Description**: Fluids entering the waste container selectively leach the fissile materials, separating them from neutron sorbers (YMP)

Primary: **Criticality in waste and EBS**
Secondary: Differential solubility of fissile isotopes

FEP Number (2.1.14.01.17)	**Originator FEP Description**: Solubilities of various fissile isotopes differ (235U vs. 239Pu). (YMP)

Primary: Criticality In-Situ, Nominal Configuration, Top Breach

FEP Number (2.1.14.02.00)	**Primary Description:** The waste package internal structures and the waste form remain intact (nominal configuration). There is a breach near the top of the waste package, which allows water to collect in the waste package. Criticality then occurs in-situ.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis**: Low probability
Number of Secondaries: *2*	

Primary: **Criticality in-situ, nominal configuration, top breach**
Secondary: Criticality - MPC flooded

FEP Number (2.1.14.02.01)	**Originator FEP Description**: This assembly is specialized to the MPC (Multi-purpose Container) and is otherwise entry 2.1.14g (YMP)

Primary: **Criticality in-situ, nominal configuration, top breach**
Secondary: Criticality - nominal configuration, partially flooded, otherwise intact

FEP Number (2.1.14.02.02)	**Originator FEP Description**: A container with holes at the top is flooded sufficiently for enough moderation to produce criticality. (YMP)

Primary: Criticality In-Situ, Waste Package Internal Structures Degrade Faster Than Waste Form, Top Breach

FEP Number (2.1.14.03.00)	**Primary Description:** The waste package internal structures degrade, but not the waste form. There is a breach near the top of the waste package, which allows standing water to collect in the waste package. Significant amounts of the neutron absorber are flushed out the top of the waste package and DSNF criticality occurs in-situ.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis**: Low Probability
Number of Secondaries: 3	

Primary: **Criticality in-situ, waste package internal structures degrade faster than waste form, top breach**
Secondary: Waste package internal structures degrade faster than waste form

FEP Number (2.1.14.03.01)	**Originator FEP Description**: Internal supporting structures (such as fuel bundle baskets) degrade faster than the waste form. (YMP)

Primary: **Criticality in-situ, waste package internal structures degrade faster than waste form, top breach**
Secondary: Waste package internal structures collapse

FEP Number (2.1.14.03.02)	**Originator FEP Description**: Internal supporting structures (such as fuel bundle baskets) collapse (YMP)

Primary: **Criticality in-situ, waste package internal structures degrade faster than waste form, top breach**
Secondary: Criticality - container partially gone, optimal rod configuration, flooded

FEP Number (2.1.14.03.03)	**Originator FEP Description**: The container has failed and allows water entry. Fuel rods are in an optimal configuration and criticality ensues. (YMP)

Primary: Criticality In-Situ, Waste Package Internal Structures Degrade At Same Rate As Waste Form, Top Breach

FEP Number (2.1.14.04.00)	**Primary Description:** The waste package internal structures degrade at the same rate as the waste form. There is a breach near the top of the waste package, which allows water to collect in the waste package. Significant amounts of the neutron absorber are flushed out the top of the waste package. A slurry with insufficient neutron absorbing material forms at the waste package bottom and criticality occurs in-situ.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low Probability
Number of Secondaries: 2	

Primary: **Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach**
Secondary: Waste package internal structures and the waste form degrade at the same rate

FEP Number (2.1.14.04.01)	**Originator FEP Description**: Internal supporting structures (such as fuel bundle baskets) and the waste form degrade at approximately the same rate. (YMP)

Primary: **Criticality in-situ, waste package internal structures degrade at same rate as waste form, top breach**
Secondary: Criticality - clad and disintegrated pellets, optimally mixed, flooded

FEP Number (2.1.14.04.02)	**Originator FEP Description**: Clad and disintegrated fuel pellets are mixed optimally in a container which is then flooded. Criticality ensues. (YMP)

Primary: Criticality In Situ, Waste Package Internal Structures Degrade Slower Than Waste Form, Top Breach

FEP Number (2.1.14.05.00)	**Primary Description:** The waste package internal structures degrade slower than waste form. There is a breach near the top of the waste package, which allows water to collect in the waste package. The waste form degrades, separating from the neutron absorbers. A slurry forms at the waste package bottom. Criticality occurs in-situ.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 1	

Primary: **Criticality in-situ, waste package internal structures degrade slower than waste form, top breach**

Secondary: Waste package internal structures degrade slower than waste form

FEP Number (2.1.14.05.01)	**Originator FEP Description**: Internal supporting structures (such as fuel bundle baskets) degrade slower than the waste form. (YMP)

Primary: Criticality In Situ, Waste Form Degrades In Place and Swells, Top Breach

FEP Number (2.1.14.06.00)	**Primary Description:** The waste package internal structures remain intact while the waste form degrades. There is a breach near the top of the waste package, which allows water to collect in the waste package. The waste form degrades in place, but swells into a more reactive configuration, which may overwhelm the in-place neutron absorbing material. Criticality occurs in-situ.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	

Primary: Criticality In Situ, Bottom Breach Allows Flow Through Waste Package, Fissile Material Collects at Bottom of Waste Package

FEP Number (2.1.14.07.00)	**Primary Description:** There is a breach at the bottom of the waste package, which does not allow water to collect in the waste package. Moderation is provided by water retained in clay or hydrated metal corrosion products accumulating in the bottom of the waste package with the fissile material. Significant amounts of the neutron absorber are either flushed from the waste package or remain distributed throughout the waste package, while fissile material collects at bottom of the waste package. Criticality occurs in-situ.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	

Primary: Criticality In Situ, Bottom Breach Allows Flow Through Waste Package, Waste Form Degrades In Place

FEP Number (2.1.14.08.00)	**Primary Description:** There is a breach at the bottom of the waste package, which does not allow water to collect in the waste package. Moderation is provided by water trapped in the clay or oxides. The waste form degrades in place and the neutron absorbing material mobilizes away from the waste form. Criticality occurs in-situ.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 3	

Primary: **Criticality in situ, bottom breach allows flow through waste package, waste form degrades in place**
Secondary: Neutron absorber system selectively degrades

FEP Number (2.1.14.08.01)	**Originator FEP Description**: Borated steel plates, designed to reduce the likelihood of criticality, selectively degrade. (YMP)

Primary: **Criticality in situ, bottom breach allows flow through waste package, waste form degrades in place**
Secondary: Neutron absorbers selectively flushed from containers

FEP Number (2.1.14.08.02)	**Originator FEP Description**: Neutron sorbers, added to the CSNF containers to control criticality, are flushed from the container. (YMP)

Primary: **Criticality in situ, bottom breach allows flow through waste package, waste form degrades in place**
Secondary: Selective leaching of neutron absorbers

FEP Number (2.1.14.08.03)	**Originator FEP Description**: Fluids entering the waste container selectively leach the neutron poisons which were added to reduce the likelihood of criticality. (YMP)

Primary: Near-Field Criticality, Fissile Material Deposited In Near-Field Pond

FEP Number (2.1.14.09.00)	**Primary Description:** Fissile material-bearing solution or intact fissile material is deposited in a near-field pond. Fissile material may migrate due to bottom-only breach of cask or due to massive structural failure of waste package. Near-field criticality can result if fissile material geometry represents critical configuration and sufficient water is present in pond.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 9	

Primary: **Near-field criticality, fissile material deposited in near-field pond**
Secondary: Criticality - container gone, intact rods, flooded

FEP Number (2.1.14.09.01)	**Originator FEP Description**: The waste container is effectively breached, but fuel rods and baskets are intact and the space surrounding is locally flooded. (YMP)

Primary: **Near-field criticality, fissile material deposited in near-field pond**
Secondary: Criticality - container gone, intact rods, dry

FEP Number (2.1.14.09.02)	**Originator FEP Description**: The waste container is effectively breached, but fuel rods and baskets are intact. The assemblies are dry. (YMP)

Primary: **Near-field criticality, fissile material deposited in near-field pond**
Secondary: Criticality - container gone, pile of fuel pellets, dry

FEP Number (2.1.14.09.03)	**Originator FEP Description**: The container, baskets and cladding have failed, leaving a pile of fuel pellets in various conditions lying where they have fallen on the drift floor. For the only moderator being iron oxide, calculations suggest that no critical assembly will form. (YMP)

Primary: **Near-field criticality, fissile material deposited in near-field pond**
Secondary: Criticality - container gone, pile of fuel pellets, flooded

FEP Number (2.1.14.09.04)	**Originator FEP Description**: The container, baskets and cladding have all failed, dumping the fuel pellets into a pile. Because of rockfall, floor heave, etc., water is trapped and the pile of fuel fragments is flooded. (YMP)

Primary: **Near-field criticality, fissile material deposited in near-field pond**
Secondary: Criticality - container and cladding gone, fuel powder, flooded

FEP Number (2.1.14.09.05)	**Originator FEP Description**: The container and cladding have corroded, dumping more or less disintegrated fuel pellets (distribution of particle sizes). The remains are flooded. (YMP)

Primary: **Near-field criticality, fissile material deposited in near-field pond**
Secondary: Criticality - container and cladding gone, pile of fuel pellets, dry

FEP Number (2.1.14.09.06)	**Originator FEP Description**: The container and cladding have corroded, dumping more or less disintegrated fuel pellets (distribution of particle sizes). Iron oxides are the only moderators present (no liquid water is present as moderator). (YMP)

Primary: **Near-field criticality, fissile material deposited in near-field pond**
Secondary: Formation of a critical assembly in a pool (in waste and EBS)

FEP Number (2.1.14.09.07)	**Originator FEP Description**: A critical assembly develops in a pool formed by floor buckling after accumulating water and fissile isotopes. (YMP)

Primary: **Near-field criticality, fissile material deposited in near-field pond**
Secondary: Pu accumulates in basin pool (in waste and EBS)

FEP Number (2.1.14.09.08)	**Originator FEP Description**: Plutonium, mobilized as colloids or solutes, accumulates in the pool in a basin produced by floor buckling or invert collapse. (YMP)

Primary: **Near-field criticality, fissile material deposited in near-field pond**
Secondary: Accumulated 239Pu decays to 235U in basin pool (in waste and EBS)

FEP Number (2.1.14.09.09)	**Originator FEP Description**: Radioactive decay changes the 239Pu accumulated in a basin pool to more soluble and mobile 235U. (YMP)

Primary: Near-Field Criticality, Fissile Solution Flows Into Drift Lowpoint

FEP Number (2.1.14.10.00)	**Primary Description:** Near-field criticality results when fissile material-bearing solution flows into a drift lowpoint. The poison has already been separated from the [solution carrying the fissile material], either due to retention in intact [componenents within the waste package] or prior removal by flow-through leaching within the waste package.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 1	

Primary: **Near-field criticality, fissile solution flows into drift lowpoint**
Secondary: Accumulation of clays and sediments in basins (in EBS)

FEP Number (2.1.14.10.01)	**Originator FEP Description**: Accumulation of sediments in the basin formed by floor buckling. (YMP)

Primary: Near-Field Criticality, Fissile Solution Is Adsorbed Or Reduced In Invert

FEP Number (2.1.14.11.00)	**Primary Description:** Near-field criticality results from fissile solution adsorbed or reduced in invert (concrete and crushed tuff). The geometry of the invert allows zonal precipitation (under the influence of gravity) wherein the fissile and non fissile species may precipitate at different places within the invert.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	

Primary: Near-Field Criticality, Filtered Slurry or Colloidal Stream Collects On Invert Surface

FEP Number (2.1.14.12.00)	**Primary Description:** Near-field criticality results when slurry or colloidal stream is filtered (i.e., neutron absorbers are removed) by waste package corrosion products and collect on top of invert surface.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	

Primary: Near-Field Criticality Associated With Colloidal Deposits

FEP Number (2.1.14.13.00)	**Primary Description:** Near-field criticality could result from colloids deposited in fractured or degraded concrete, from colloids filtered in the invert, or from colloids deposited in dead-ends of stress-relief cracks in the surrounding tunnel.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	

Primary: Out-of-Package Criticality, Fuel/Magma Mixture

FEP Number (2.1.14.14.00)	**Primary Description:** Interaction between fuel and magma dilutes fissile material, excludes water, and minimizes its return. For criticality to occur, neutron absorbers must also be removed.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	

Primary: Critical Assembly Forms Away From Repository

FEP Number (2.2.14.01.00)	**Primary Description:** Nuclear criticality requires a sufficient concentration and localized (critical) mass of fissile isotopes (e.g., U-235, Pu-239) and also the presence of neutron moderating materials (e.g., water) in a suitable geometry. Criticality is liable to be damped by the presence of neutron absorbing isotopes (e.g., Pu-240). Far-field criticality can occur if fissile material is transported away from the repository and then a critical mass accumulates in the presence of water. This FEP aggregates all mechanisms for far-field criticality into a single category. Specific processes that could produce far-field criticality are discussed in FEPs [2.2.14.02.00 through 2.2.14.08.00.]
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 4	

Primary: **Critical assembly forms away from repository**
Secondary: Reconcentration (release/migration factors)

FEP Number (2.2.14.01.01)	**Originator FEP Description**: The only interpretation of this process is the accumulation by precipitation or sorption of radionuclides within a rather confined volume along the path to the biosphere. Subsequent release by changes chemistry might then give a kind of pulse discharge too the environment. (Joint SKI/SKB)

Primary: **Critical assembly forms away from repository**
Secondary: Reconcentration (release/migration factors)

FEP Number (2.2.14.01.02)	**Originator FEP Description**: The only interpretation of this process is the accumulation by precipitation or sorption of radionuclides within a rather confined volume along the path to the biosphere. Subsequent release by changed chemistry might then give a kind of pulse discharge to the environment. etc. (SKI)

Primary: **Critical assembly forms away from repository**
Secondary: DOE SNF criticality far-field (radionuclide inventory impact)

FEP Number (2.2.14.01.03)	**Originator FEP Description**: The DOE SNF to be disposed of in Yucca Mountain might have the potential to result in a criticality in the far-field region, if selective transport of fissile material occurs and other conditions are met. A criticality event could increase the radionuclide inventory available for groundwater transport. This FEP was obtained from Reference 1 and is identified as MLD-4 in that reference.

Primary: **Critical assembly forms away from repository**
Secondary: DOE SNF criticality far-field (waste heat impact)

FEP Number (2.2.14.01.04)	**Originator FEP Description**: The DOE SNF to be disposed of in Yucca Mountain might have the potential to result in a criticality in the far-field region, if selective transport of fissile material occurs and other conditions are met. A criticality event could increase the waste heat generation during the event, thereby affecting thermal hydrology and seepage onto the waste packages. This FEP was obtained from Reference 1 and is identified as MLD-10 in that reference.

Primary: Far-Field Criticality, Precipitation In Organic Reducing Zone In Or Near Water Table

FEP Number (2.2.14.02.00)	**Primary Description:** Fissile material is transported to an organic reducing zone and precipitates in a geometrically favorable configuration in or near water table.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 2	

Primary: **Far-field criticality, precipitation in organic reducing zone in or near water table**
Secondary: Precipitation of U at reducing zone associated w/organics in alluvial aquifer

FEP Number (2.2.14.02.01)	**Originator FEP Description**: Dissolved Uranium is precipitated by interaction with organic materials which have accumulated in the alluvial aquifer. (YMP)

Primary: **Far-field criticality, precipitation In organic reducing zone in or near water table**
Secondary: Precipitation of U at reducing zone associated w/organics in Franklin Lake playa

FEP Number (2.2.14.02.02)	**Originator FEP Description**: Dissolved Uranium is precipitated by interaction with organic materials which have accumulated in Franklin Lake playa. (YMP)

Primary: Far-Field Criticality, Sorption On Clay/Zeolite In TSbv

FEP Number (2.2.14.03.00)	**Primary Description:** Fissile material is transported to Topopah Springs unit where it sorbs onto the clays and zeolites of the basal vitrophyre in a geometrically favorable configuration.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	

Primary: Far-Field Criticality, Precipitation Caused By Hydrothermal Upwell Or Redox Front In The SZ

FEP Number (2.2.14.04.00)	**Primary Description:** Fissile material is transported to the SZ where it encounters hydrothermal upwelling or a redox front and precipitates in a geometrically favorable configuration in the SZ.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 2	

Primary: **Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ**
Secondary: Precipitation of U in the upwelling zone along some faults

FEP Number (2.2.14.04.01)	**Originator FEP Description**: Dissolved Uranium is precipitated in the upwelling zones which have been identified along the Solitario Canyon Fault and the Bow Ridge Fault to the south of the repository block. (YMP)

Primary: **Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ**
Secondary: Precipitation of U below the redox front in the SZ

FEP Number (2.2.14.04.02)	**Originator FEP Description**: Dissolved Uranium is precipitated when mixed below the redox front, which has been identified about 200m below the water table in the SZ. (YMP)

Primary: Far-Field Criticality, Precipitation In Perched Water Above TSbv

FEP Number (2.2.14.05.00)	**Primary Description:** Fissile material is transported to the perched water above the Topopah Springs basal vitrophyre, where chemical change causes it to precipitate in a geometrically favorable configuration.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 1	

Primary: **Far-field criticality, precipitation in perched water above TSbv**
Secondary: Accumulation of solute in topographic lows of the altered TSbv

FEP Number (2.2.14.05.01)	**Originator FEP Description**: The upper surface of the altered Topopah Spring basal vitrophyre (see 2.2.08ba) has relief which results in local lows which accumulate perched water, which contains contaminants. (YMP)

Primary: Far-Field Criticality, Precipitation In Fractures of TSw Rock

FEP Number (2.2.14.06.00)	**Primary Description:** Fissile material is transported to Topopah Springs welded unit where it precipitates in a geometrically favorable configuration within the fractures.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	

Primary: Far-Field Criticality, Dryout Produces Fissile Salt In A Perched Water Basin

FEP Number (2.2.14.07.00)	**Primary Description:** Fissile material is transported to a perched water basin. Dryout (evaporation exceeds infiltration) of the basin and the solution containing fissile material results in a fissile salt in a geometrically favorable configuration in the basin.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	

Primary: Far-Field Criticality Associated With Colloidal Deposits

FEP Number (2.2.14.08.00)	**Primary Description:** Far-field criticality could result from colloids deposited in clays/zeolites in TSbv or deposited in perched water above the relatively impermeable TSbv.
Primary Assigned to: *Criticality FEPs*	
Screening Decision: *Excluded* from the TSPA–SR (Preliminary)	**Screening Decision Basis**: Low probability
Number of Secondaries: 0	