# ISSUE RESOLUTION STATUS REPORT

# KEY TECHNICAL ISSUE: TOTAL SYSTEM PERFORMANCE ASSESSMENT AND INTEGRATION

**Division of Waste Management**
**Office of Nuclear Material Safety and Safeguards**
**U.S. Nuclear Regulatory Commission**

**Revision 3**

**September 2000**

**Change History of "Issue Resolution Status Report (IRSR), Key Technical Issue: Total System Performance Assessment and Integration (TSPAI)"**

| Revision | Section | Date | Modification |
|---|---|---|---|
| Rev. 0 | All | April 1998 | None. Initial Issue. |
| Rev. 1 | All | November 1998 | General editorial changes. |
| Rev. 1 | 1.0 | November 1998 | Updated text on issue resolution. |
| Rev. 1 | 2.0 | November 1998 | Added discussion for two new subissues. |
| Rev. 1 | 3.2 | November 1998 | Modified to reflect two new subissues. |
| Rev. 1 | 4.0 | November 1998 | Programmatic acceptance criteria moved from Section 4.1 of Rev. 0. |
| Rev. 1 | 4.1 | November 1998 | Added placeholder for new subissue: compliance with overall performance objective. |
| Rev. 1 | 4.2 | November 1998 | Added placeholder for new subissue: demonstration of multiple barriers. |
| Rev. 1 | 4.3 | November 1998 | Programmatic acceptance criteria moved to Section 4.0; pertinent subissues updated to reflect changes to other IRSRs; "laboratory data" replaces "experimental data" in acceptance criteria T1. |
| Rev. 1 | 4.3.1.1.1 | November 1998 | Updated technical basis to reflect changes to DOE's reference design and behavior of Alloy C-22. |
| Rev. 1 | 4.3.1.1.2 | November 1998 | Updated technical basis to reflect new NRC modeling approaches to rockfall and fault displacement and to staff perspectives on phenomena related to mechanical failure of waste packages. |
| Rev. 1 | 4.3.1.1.4 | November 1998 | Updated technical basis to reflect new NRC modeling approaches to radionuclide releases from waste packages. |

**Change History of "Issue Resolution Status Report (IRSR), Key Technical Issue: Total System Performance Assessment and Integration (TSPAI)" (cont'd)**

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|---|---|---|---|
| Rev. 1 | 4.3.2.1.1 | November 1998 | Updated introduction and technical basis. |
| Rev. 1 | 4.3.2.1.3 | November 1998 | Updated technical basis. |
| Rev. 1 | 4.3.2.2.1 | November 1998 | Updated technical basis. |
| Rev. 1 | 4.3.2.3.1 | November 1998 | Updated technical basis. |
| Rev. 1 | 4.3.2.3.2 | November 1998 | Updated technical basis. |
| Rev. 1 | 4.4 | November 1998 | Added acceptance criteria, review methods, and technical basis to address scenario analysis. |
| Rev. 1 | 4.5 | November 1998 | Moved from Section 4.2. |
| Rev. 1 | 5.0 | November 1998 | Updated status of scenario analysis Open Items. |
| Rev. 1 | Appendix B | November 1998 | Updated to reflect new subissues. |
| Rev. 1 | Appendix C | November 1998 | Updated to reflect changes to NRC total system performance assessment models. |
| Rev. 1 | Appendix D | November 1998 | Added to illustrate expected dose calculation. |
| Rev. 2 | All | January 2000 | General editorial changes. |
| Rev. 2 | 1.0 | January 2000 | Updated text on issue resolution. |
| Rev. 2 | 2.0 | January 2000 | Updated to reflect new subissues. |
| Rev. 2 | 3.2 | January 2000 | Updated to reflect new subissues. |
| Rev. 2 | 4.1 | January 2000 | Updated to new subissue; added acceptance criteria and review methods for transparency and traceability added. |
| Rev. 2 | 4.2 | January 2000 | Moved from Section 4.4 based on new subissues; discussion on Open Items added. |

**Change History of "Issue Resolution Status Report (IRSR), Key Technical Issue: Total System Performance Assessment and Integration (TSPAI)" (cont'd)**

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|---|---|---|---|
| Rev. 2 | 4.3 | January 2000 | Moved discussion added to Criterion T1 on the use of Expert elicitation and bounding values where data does not exist; validation replaced with justification in Criterions T2 and T4; discussion on Open Items added. |
| Rev. 2 | 4.3.1.1.1 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.1.1.2 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.1.1.3 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.1.1.4 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.2.1.1 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.2.1.2 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.2.1.3 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.2.2.1 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |

**Change History of “Issue Resolution Status Report (IRSR), Key Technical Issue: Total System Performance Assessment and Integration (TSPAI)” (cont’d)**

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|---|---|---|---|
| Rev. 2 | 4.3.2.2.2 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.2.3.1 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.2.3.2 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.3.1.1 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.3.1.2 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.3.3.1.3 | January 2000 | Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation. |
| Rev. 2 | 4.4 | January 2000 | Moved from Section 4.1 based on new subissues; Updated example calculation of expected annual dose and moved to this section; Added discussion on Open Items. |
| Rev. 2 | 4.5 | January 2000 | Moved to Section 4.1. |
| Rev. 2 | 5.0 | January 2000 | Updated status of Open Items and discussion points. |
| Rev. 2 | Appendix B | January 2000 | Updated to reflect new subissues. |
| Rev. 2 | Appendix C | January 2000 | New section describing the NRC technical bases for the integrated subissues. |

**Change History of "Issue Resolution Status Report (IRSR), Key Technical Issue: Total System Performance Assessment and Integration (TSPAI)" (cont'd)**

| | | | |
|---|---|---|---|
| Rev. 2 | Appendix D | January 2000 | Moved from Appendix C. Updated to reflect changes to NRC total system performance assessment models. |
| Rev. 3 | 4.0 | July 2000 | Removed acceptance criteria and review methods—will be presented in Yucca Mountain Review Plan (YMRP). |
| Rev. 3 | 4.0 | July 2000 | Added technical basis for two subissues: (i) system description and demonstration of multiple barriers and (ii) demonstration of the overall performance objectives. |
| Rev. 3 | 4.0 | July 2000 | Moved description and analysis of the DOE Approach to Chapter 5. |
| Rev. 3 | 5.0 | July 2000 | Changed Tables 18, and 19 to Tables 1 and 6. Deleted Table 17. |
| Rev. 3 | 5.0 | July 2000 | Condensed Tables 20–33 and moved to Table 5 in the new version. |
| Rev. 3 | Appendix A | July 2000 | Relevant hypothesis in DOE's Repository Safety Strategy (RSS) replaced with DOE principal factors in Revision 3 and 4 (proposed) of the RSS. |
| Rev. 3 | Appendix B | July 2000 | Updated to reflect current list of subissues in NRC key technical issues. |
| Rev. 3 | Appendix C (old) | July 2000 | Moved Technical Basis for review of the integrated subissues from Appendix C to Chapter 5. |
| Rev. 3 | Appendix D (old) | July 2000 | Appendix D (Summary of the conceptual approaches in TPA Version 3.2 code for the integrated subissues) changed to Appendix F. |
| Rev. 3 | Appendixes C, D, and E | July 2000 | Added summary of review results for the features, events, and processes (FEPs) for criticality, biosphere, and orphan FEPs, respectively. |

## EXECUTIVE SUMMARY

The Total System Performance Assessment and Integration (TSPAI) Key Technical Issue (KTI) deals with review of performance of the repository system during the regulatory time period of compliance. U.S. Nuclear Regulatory Commission (NRC) staff relies on its TSPAI KTI activities to (i) evaluate the DOE Total System Performance Assessment (TSPA) to support Site Recommendation (SR) and provide a basis for NRC's sufficiency comments, (ii) facilitate constructive review and comment on DOE's Draft Environmental Impact Statement, (iii) prepare for an effective and efficient review of a potential license application, and (iv) provide quantitative analyses of the repository system. In light of risk-informed and performance-based regulations, the NRC staff will evaluate critical portions of the DOE TSPA to determine compliance with regulatory requirements.

Revision 3 of this Issue Resolution Status Report (IRSR) describes the technical bases for NRC's review of DOE's demonstration of repository performance. This IRSR evaluates the DOE TSPA methodology and analysis approach to demonstrate compliance with regulatory requirements and the IRSR also defines the current status and path to resolution of four subissues in the TSPAI KTI. A summary of the status of Open Items is provided in the following table. This IRSR also includes a review of features, events, and processes (FEPs) related to biosphere and nuclear criticality together with a review of those FEPs not covered by other KTIs. This revision reflects NRC's understanding of the DOE Repository Safety Strategy (Revision 3) and information available to NRC through release of the DOE TSPA Methods and Assumption report, several AMRs and PMRs (some are drafts), and information gathered at the DOE/NRC Technical Exchange on TSPA held June 6–7, 2000.

The model abstraction section uses 14 integrated subissues (ISIs) to emphasize that a high level of integration is necessary to evaluate a complex process containing many components. The specific disciplines involved in the evaluation of an ISI are defined by the KTI subissues associated with an ISI. NRC's review of model abstraction, except for the section on status of resolution for degradation of engineered barriers, has not been updated beyond the Viability Assessment. The next revision of this report will update NRC's technical basis for model abstraction and provide a status on NRC's evaluation of DOE's approach to abstraction for all integrated subissues.

| Subissue | Status | Path to Resolution |
|---|---|---|
| System Description and Demonstration of Multiple Barriers | Open | Information required on: (i) reliance on barriers in a semi-quantitative or quantitative manner; (ii) treatment of uncertainty in barrier performance; and (iii) use of barrier importance to determine extent of technical basis needed to support barrier capability; All TSPA-SR documentation must be sufficiently transparent and traceable. |

| Subissue | Status | Path to Resolution |
|---|---|---|
| Scenario Analysis | Open | Information required on: (i) comprehensiveness and technical completeness of FEPs Database; (ii) adequacy of justification; (iii) screening arguments; and (iv) technical bases. General improvement required in documentation for sufficient transparency and traceability. |
| Model Abstraction | Open | Each ISI must satisfy generic model abstraction acceptance criteria to be closed prior to potential license application. Information required on: (i) data and model justification; (ii) data uncertainty; (iii) model uncertainty; (iv) model support; and (v) integration. The TSPAI KTI will focus on integration and on model implementation (in particular, propagation of uncertainties). Process KTIs will focus on other generic acceptance criteria. The TSPAI KTI path forward will be to review all abstraction AMRs and the TSPA-SR, when available. The TSPAI KTI will then provide specific items to be resolved to close model abstraction. |
| Demonstration of the Overall Performance Objective | Open | Information required on: (i) implementation of the methodology to calculate expected annual dose for all scenario classes; (ii) demonstration that sufficient number of realizations are conducted; (iii) treatment of model uncertainty in TSPA; (iv) approach for demonstration of reasonable or conservative representation of actual repository performance; (v) sufficiency of treatment of alternative conceptual models in TSPA calculations; and (vi) comparison of alternate repository designs. |

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**QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT**: There are no original data contained in this report. No computer codes were used for analyses presented in this report. Other calculations, such as hand calculations, meet quality assurance requirements described in the CNWRA Quality Assurance Manual.

## 1.0 INTRODUCTION

U.S. Nuclear Regulatory Commission's (NRC's) strategic plan calls for the early identification and resolution, at the staff level, of issues before the receipt of a potential license application (LA) to construct a geologic repository. The principal means for achieving this goal is through prelicensing consultation with the U.S. Department of Energy (DOE). These consultations, required by the Nuclear Waste Policy Act of 1982 (NWPA), occur in an open manner that permits observation by the State of Nevada, Tribal Nations, affected units of local government, and interested members of the public. Obtaining input and striving for consensus from the technical community and interested parties help the issue resolution process. Staff issue resolution during the preliminary consultation period is included in the proposed regulation specified in 10 CFR Part 63. This process of prelicensing issue resolution attempts to avoid having subissues in dispute at the time of the NRC's licensing review.

Consistent with NRC regulations and a 1992 agreement with the DOE, staff-level issue resolution can be achieved during the prelicensing consultation period. The three categories of issue resolution defined by the NRC are:

- Closed—Issues are considered to be "closed" if the DOE approach and available information acceptably addresses staff questions such that no information beyond what is currently available will likely be required for regulatory decision making at the time of initial license application.

- Closed, pending additional information—Issues are considered to be "closed-pending" if the NRC staff has confidence that the DOE proposed approach, together with the DOE agreement to provide the NRC with additional information (through specified testing, analysis, etc.) acceptably addresses the NRC's questions such that no information beyond that provided, or agreed to, will likely be required at time of initial license application.

- Open—Issues are considered to be "open" if the NRC has identified questions regarding the DOE approach or information, and the DOE has not yet acceptably addressed the questions or agreed to provide the necessary additional information in the license application.

It should be noted that additional pertinent information could raise new questions or comments regarding a previously resolved issue. The issue may be re-opened and considered during licensing proceedings.

NRC's high-level radioactive waste (HLW) program was realigned during fiscal year (FY) 1996–1997. The realignment was in response to: (i) a reduction in Congressional budget appropriations for NRC in FY 1996; (ii) the reorganization of DOE's geologic repository program at Yucca Mountain (YM), Nevada; and (iii) a 1995 report issued by the National Academy of Sciences (NAS) to advise the U.S. Environmental Protection Agency (EPA) regarding the technical bases for new geologic disposal standards for YM. In response to these developments, the NRC HLW program was realigned to focus prelicensing work on those topics most critical to the post-closure performance of the proposed geologic repository; these topics are called Key Technical Issues (KTIs). [This approach is summarized in Chapter 1 of the staff's FY 1996 Annual Progress Report (see Sagar, 1997).]

The current Division of Waste Management (DWM) approach is to focus most activities on issue resolution of the respective KTIs, at the staff level. DWM activities have been reprioritized to streamline and improve the integration of the technical work necessary to achieve staff-level resolution. Integration of KTI activities into a risk-informed approach and evaluation of their significance for postclosure repository performance help ensure that regulatory attention is focused where technical uncertainties will have the greatest effect on the assessment of repository safety, and all elements of the regulatory program are consistently focused on these areas. Early feedback among all parties is essential to define what is known, what is not known and where additional information is likely to make a significant difference in the understanding of future repository safety.

An important step in the staff's approach to issue resolution is to provide DOE with feedback regarding issue resolution before the forthcoming Site Recommendation (SR) and LA. Issue Resolution Status Reports (IRSRs) are the primary mechanism that the NRC staff will use to provide DOE with feedback on KTI subissues. IRSRs focus on the status of resolution of acceptance criteria for issue resolution, including areas of agreement or when the staff has comments or questions. Additionally, open meetings and technical exchanges with DOE provided, and will continue to provide, additional opportunities to discuss issue resolution, identify areas of agreement and disagreement, and develop plans to resolve such disagreements. Finally, the staff is currently developing a risk-informed and performance-based Yucca Mountain Review Plan (YMRP) for a potential YM repository LA based primarily on the acceptance criteria found in previous IRSRs.

This IRSR contains six chapters, including this introductory chapter. Chapter 2.0 defines the KTI, related subissues, and scope of the subissues addressed in the IRSR. Chapter 3.0 discusses the importance of the subissues to evaluation of repository performance. Chapter 4.0 provides the technical basis for resolution of the subissues that will be used by the staff in subsequent reviews of DOE submittals. With this revision (Revision 3), the acceptance criteria and review methods for evaluating DOE's approach to abstracting and analyzing KTIs in a Total System Performance Assessment (TSPA) have been moved to the YMRP. The acceptance criteria are guidance for the staff and, indirectly, for DOE as well. The application of specific acceptance criteria to recent information provided by DOE regarding the SR is presented in Chapter 5.0 with updated status of resolution of subissues. Chapter 6.0 contains a list of pertinent references.

Table 1 documents the status of resolution of the Total System Performance Assessment and Integration (TSPAI) KTI Open Items. These Open Items will continue to be tracked by the staff and resolution will be documented in future IRSRs. Appendix A maps integrated subissues (ISIs) (See Section 4.3 for definition) to DOE principal factors. Appendix B lists the subissues in NRC KTIs. Appendixes C and D provide summaries of review results for nuclear criticality (near- and far-field) and biosphere primary features, events, and processes (FEPs),

**Table 1. Summary of Total System Performance Assessment and Integration Key Technical Issue Open Item status**

| Item ID | Status | Title | Comment |
|---|---|---|---|
| OAO030SEP1992C001 | Resolved | Possible occurrences of potential disruptive processes and events and effects on postclosure performance | See TSPAI IRSR, Rev 2, Table 18 |
| OAO030SEP1992C002 | Resolved | Pre-closure potentially disruptive events used as examples of potential postclosure effects on performance | See TSPAI IRSR, Rev 2, Table 18 |
| OAO017APR1992C003 | Resolved | Misplacement of discussion on performance assessments to address 40 CFR 191.13 | 40 CFR 191.13 no longer applicable to YM |
| OSC0000001347C003 | Resolved | Reliance on formal use of expert judgment in place of quantitative analysis may lead to incomplete License Application | Bell (1998a) |
| OSC0000001347C022 | Resolved | Inadequate saturated zone hydrology sample collection methods | Bell (1998b) |
| OSC0000001347C100 | Resolved | Performance assessment: adequacy of considerations of faulting release scenarios | NRC (1989), DOE (1990), Bernero (1991), Roberts (1992), Holonich (1993) |
| OSC0000001347C101 | Resolved | The equation (8.3.5.13-21) used to estimate the partial performance measure for the $j^{th}$ scenario class involving water pathway releases may be in error | Austin (1996) |
| OSC0000001347C103 | Resolved | The Ross sequence numbers 59 through 62 and 64 through 69 do not characterize scenarios | Austin (1996) |

**Table 1. Summary of Total System Performance Assessment and Integration Key Technical Issue Open Item status (cont'd)**

| Item ID | Status | Title | Comment |
|---|---|---|---|
| OSC0000001347C104 | Resolved | Scenario analysis appears to have omitted vitrified high-level waste | NRC (1989), DOE (1990), Bernero (1991), Roberts (1992), Holonich (1993) |
| OSC0000001347C107 | Resolved | The use of waiting time may preclude accurate representation of clustered phenomena | Benero (1991) |
| OSC0000001347C108 | Resolved | Concerns about the use of the expected partial performance measure to screen scenarios | Holonich (1992, 1993), Roberts (1992) |
| OSC0000001347C110 | Resolved | SCP text is unclear how human intrusion will be handled | Holonich (1992, 1993); Roberts (1992) |
| OSC0000001347C111 | Resolved | Inconsistencies in Total System Performance Section of SCP | Benero (1991) |
| OSC0000001347C112 | Resolved | A gap exist in the discussion of the treatment of state variables as constants or as random variables | Roberts (1992); Holonich (1993) |
| OSC0000001347C113 | Resolved | Inconsistent definitions of the unit step function and of the CCDF | Holonich (1992, 1993); Roberts (1992) |
| OSC0000001347C114 | Resolved | Incorrect use of the term *independent* in place of *mutually exclusive* | Benero (1991) |
| OSC0000001347C115 | Resolved | Statement that CCDF scenario classes can only be expanded if entities are independent is incorrect | Austin (1996) |
| OSC0000001347Q048 | Resolved | Question selection procedures for peer-review panel | Benero (1991) |

**Table 1. Summary of Total System Performance Assessment and Integration Key Technical Issue Open Item status (cont'd)**

| Item ID | Status | Title | Comment |
|---|---|---|---|
| OAO028MAY1993C001 | Resolved | PACs may not be appropriately considered in compliance demonstration with overall performance objectives | See TSPAI IRSR, Rev. 2, Table 18 |
| OAO028MAY1993C002 | Resolved | Consideration of present PACs/FACs may be inappropriately restricted to scenario development | See TSPAI IRSR, Rev. 2, Table 18 |
| OSC0000001347C001 | Resolved | Incomplete program for Issue Resolution Strategy | NRC (1989), DOE (1990); Bernero (1991). See TSPAI IRSR, Rev. 2, Table 18 |
| OSC0000001347C002 | Resolved | Deficiencies in performance allocation | See TSPAI IRSR, Rev. 2, Table 18 |
| OSC0000001347C116 | Resolved | Incorrect assumption that absence of significant sources of groundwater sources at site precludes consideration of environmental pathways for individual dose calculations | See TSPAI IRSR, Rev. 2, Table 18 |
| OSC0000001347C117 | Resolved | Current approach for $^{14}C$ exposure will not provide the information needed to calculate residence time | See TSPAI IRSR, Rev. 2, Table 18 |
| OSC0000001347Q022 | Resolved | Rationale for selection of performance goals needed for establishing that technologies pertaining to repository construction, operation, closure, and decommissioning are sufficiently … | Will be resolved in the RDTME IRSR |
| OSC0000001347C102 | Resolved | Performance assessment flow models are inconsistent with current understanding of site hydrology | See TSPAI IRSR, Rev. 2, Table 18 |

**Table 1. Summary of Total System Performance Assessment and Integration Key Technical Issue Open Item status (cont'd)**

| Item ID | Status | Title | Comment |
|---|---|---|---|
| OSC0000001347C099 | Resolved | Premature limiting of the total system performance consequence analysis may distort performance allocation | NRC (1989), DOE (1990), Bernero (1991), Shelor (1993), Holonich (1994); See TSPAI IRSR, Rev. 2, Table 18 |
| OSC0000001347C009 | Resolved | Lack of criteria for using expert judgment and lack of traceable and defendable procedures for expert judgment elicitation | See discussion in Section 5.2.2 |
| OSC0000001347C095 | Resolved | Underlying logic for, and implementation of, scenario development and screening are deficient for generating a CCDF and for guiding site characterization | NRC (1989), DOE (1990), Bernero (1991), Austin (1996); see discussion in Section 5.2.2 |
| OSC0000001347C105 | Resolved | Data, analyses, or justification should be provided to substantiate elimination of scenarios | NRC (1989), DOE (1990), Bernero (1991), Austin (1996); see discussion in Section 5.2.2 |
| OSC0000001347C007 | Resolved | Clarification of role of subjective methods in performance assessment is needed | See discussion in Section 5.2.2 |
| OSC0000001347C098 | Open | Weighting alternative conceptual models according to judgment that they are correct does not provide a conservative estimate of performance | NRC (1989), DOE (1990), Bernero (1991); SDS is also evaluating this Open Item; see discussion in Section 5.3.1 |

respectively. Although criticality FEPs are treated in several other IRSRs, this IRSR discusses those FEPs for comprehensiveness. Appendix E summarizes review results for FEPs not reviewed under other KTIs (referred to as “orphan” FEPs in this IRSR). Finally, Appendix F summarizes the conceptual approaches in the Total-system Performance Assessment (TPA) Version 4.0 code. This code represents one of the tools that will be used in the NRC review of the DOE TSPA approach in SR and LA.

The IRSRs were the basis for the staff’s review of information in DOE’s Viability Assessment (VA) (U.S. Department of Energy, 1998a). NRC’s comments on the VA were intended to facilitate DOE’s efforts to focus its program and develop a high-quality LA. NRC reviewed the preliminary design concept, the TSPA, the LA plan, and supporting documents. Through these reviews, NRC identified a set of technical comments regarding the Total System Performance Assessment–Viability Assessment (TSPA-VA). In this revision of the IRSR, staff’s review focused on documents currently being developed by the DOE to support the SRCR (several are draft documents, preliminary documents, or both). The draft documents include analysis model reports (AMRs), process model reports (PMRs), TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a), Repository Safety Strategy (CRWMS M&O, 2000a), and the Features, Events, and Processes (FEPs) Database (U.S. Department of Energy, 1999a). The next revision of this IRSR will provide an update of NRC’s understanding of DOE’s approach for the safety case as these documents and database are released in final form.

## 2.0 TOTAL SYSTEM PERFORMANCE ASSESSMENT AND INTEGRATION KEY TECHNICAL ISSUE AND SUBISSUES

DOE's demonstration of compliance with applicable standards for disposal of HLW in a geologic repository at YM will be based, in part, on an assessment of performance of the repository system over the specified time of compliance. The objective of the TSPAI KTI and this IRSR is to describe an acceptable methodology for conducting assessments of repository performance and using these assessments to demonstrate compliance with the overall performance objective and requirements for multiple barriers. The prescribed methodology identified herein and related acceptance criteria presented in the YMRP will be used to review DOE's TSPAs and, eventually, resolve subissues associated with DOE's demonstration of compliance with EPA standards. Standards currently being developed by EPA for the YM site are expected to require the proposed repository to meet an annual dose limit to a clearly defined receptor group. In determining whether DOE has demonstrated compliance with such standards, the NRC, using acceptance criteria that will be described in the YMRP, will review DOE's TSPA. In addition, NRC staff will evaluate critical portions of DOE's performance assessment by conducting an independent analyses.

TSPAs for a geologic repository must consider, for a given engineered design, the behavior of the engineered system, important site features, combinations of disruptive events, coupling of physical processes, and possible changes to the flow and transport system. To ensure that the risk to public health and safety from a repository is quantified and understood, repository performance must be reflected in the modeling from a total system perspective. Examples of complex phenomena that need be addressed in a TSPA include but are not limited to (i) distribution of water in the repository and how this distribution can change with time due to climate cycles, the redistribution of heat, and unsaturated zone flow processes; (ii) quantification of thermal (T), hydrologic (H), mechanical (M), and chemical (C) processes in the near field of the waste package (WP) and determination of how these processes may interact with each other to affect WP corrosion and radionuclide (RN) release; (iii) identification and incorporation of disruptive processes that could potentially breach the WPs and lead to RN release into the geosphere; (iv) assessment of how RNs that have been released from the engineered system into the geosphere will be transported and mixed in the aquifer system; and (v) evaluation of the potential exposure pathways through the biosphere (such as well pumping) and the resultant dose to humans. It can be seen from these examples that a critical aspect of an acceptable TSPA is the integration of information from many technical disciplines in the modeling and abstraction of the engineered and natural systems. The need to adequately address this integration of technical disciplines in the development of a TSPA is specifically addressed in this IRSR. Addressing the integration acceptance criterion in this IRSR is to ensure that in issue resolution and the eventual LA, the transfer of information among the technical disciplines and to DOE's TSPA occurs, the analysis is focused on the integrated total system assessment, and the assessment is transparent, traceable, defensible, and comprehensive. The analyses must also be consistent with their use to demonstrate compliance with the overall performance objective and the requirement for multiple barriers.

To achieve the stated objective, the TSPAI KTI and this IRSR concentrate on those aspects of the TSPA methodology needed to build an acceptable safety case and demonstrate compliance. The following subissues, addressed in detail in this IRSR, reflect the staff's views of those key aspects of a Total-System Performance Assessment.

- System Description and Demonstration of Multiple Barriers—This subissue focuses on the demonstration of multiple barriers and includes: (i) identification of design features of the engineered barrier system (EBS) and natural features of the geologic setting that are considered barriers important to waste isolation; and (ii) descriptions of the capability of barriers to isolate waste. In addition, it addresses the staff's expectation of the contents of DOE's TSPA and the supporting documents. Specifically, it focuses on those aspects of the TSPA that will allow for an independent analysis of the results.

- Scenario Analysis—This subissue considers the process of identifying possible processes and events that could affect repository performance; assigning probabilities to categories of events and processes; and the exclusion of processes and events from the performance assessment (PA). This is a key factor in ensuring the completeness of a TSPA.

- Model Abstraction—This subissue focuses on the information and technical needs related to the development of abstracted models for TSPA. Specifically, the following aspects of model abstraction are addressed in this subissue: (i) data used in development of conceptual approaches or process-level models that are the basis for abstraction in a TSPA, (ii) resulting abstracted models used to perform the TSPA, and (iii) overall performance of the repository system as estimated in a TSPA. In particular, this subissue addresses the need to incorporate numerous FEPs into the PA and the integration of those factors to ensure a comprehensive analysis of the total system.

- Demonstration of the Overall Performance Objective—This subissue focuses on the role of the PA to demonstrate that the overall performance objectives have been met with reasonable assurance. This subissue includes issues related to the calculation of the expected annual dose to the average member of the critical group and the consideration of parameter uncertainty, alternate conceptual models, and the results of scenario analysis.

Revision 0 of this IRSR addressed the input information and model abstraction parts of Subissue 3 (Model Abstraction). Revision 1 of the IRSR was an update of the model abstraction acceptance criteria, review methods, and technical basis for the acceptance criteria and added acceptance criteria for scenario analysis. Revision 2 of the IRSR was an update of the model abstraction and scenario analysis acceptance criteria, review methods, and technical basis for the acceptance criteria and added acceptance criteria for the transparency and traceability of DOE's analysis in system description and demonstration of multiple barriers. The updated components of the model abstraction section represented a collective effort by the NRC technical staff to integrate information from the other (non-TSPAI) KTI IRSRs. Revision 3 of the IRSR includes: (i) technical basis for system description and demonstration of multiple barriers and the use of PA to support demonstration of compliance with the overall performance objective; (ii) an updated status of resolution at the staff level for all subissues in this IRSR; (iii) results of review of FEPs related to biosphere, criticality, as well as those FEPs not contained by other KTIs; and (iv) an update of the components of the model abstraction reflecting the Enhanced Design Alternative (EDA)-II design and DOE Repository Safety Strategy (RSS) (CRWMS M&O, 2000a). The revisions reflect NRC understanding of the DOE RSS (Revision 3), and the comments are based on information made available to NRC through the release of the DOE TSPA Methods and Assumption report (CRWMS M&O, 1999a), several draft and final AMRs and PMRs, and information gathered at the DOE/NRC Technical Exchange on TSPA held June 6–7, 2000.

Currently, the EPA has not finalized standards for YM, and the NRC has not finalized implementing regulations. When the standards and implementing regulations for YM are finalized, the IRSR will be revised to ensure consistency.

## 2.1 THE ROLE OF PERFORMANCE ASSESSMENT IN RISK-INFORMING THE REVIEW OF A LICENSE APPLICATION

Performance assessment quantifies repository performance to demonstrate compliance with the postclosure performance objectives of proposed 10 CFR Part 63. The DOE performance assessment is a systematic analysis that answers the risk triplet questions: what can happen?; how likely is it to happen?; and what are the consequences? Because performance assessment encompasses a broad range of issues, risk information will be utilized throughout the review process. The use of risk information will ensure the review focuses on those items most important to performance. Performance assessment is viewed as a primary source of risk information.

The DOE must identify the important barriers (engineered and natural) for the performance assessment, describe each barriers's capability, provide the technical bases for that capability, and describe the extent of reliance on each barrier in meeting the overall performance objective. This risk information includes DOE's understanding of each barrier's importance. Staff review of the DOE barrier analysis considers risk insights from previous performance assessments conducted for the Yucca Mountain site, detailed process-level modeling efforts, laboratory and field experiments, and natural analog studies. The result of the review is a staff understanding of each barrier's importance to waste isolation. Performance assessment and process-level staff members will need to ensure that uncertainties in model abstractions are appropriately represented in barrier analysis calculations.

Scenario analysis and model abstraction are key aspects of the performance assessment. The risk information drawn from the review of the multiple barriers information will direct the staff's review to those topics within scenario analysis and model abstraction that are most important to waste isolation. An acceptable scenario selection method includes identification and classification, screening, and construction of scenarios from the features, events, and processes relevant for Yucca Mountain. Then, abstracted models are developed and implemented in the performance assessment model. The NRC divides the performance assessment into fourteen model abstractions. These model abstractions are derived from those aspects of the engineered, geosphere, and biosphere subsystems shown to be most important to performance based on prior performance assessments, knowledge of site characteristics, and repository design. The staff has developed each of the fourteen abstractions in substantial detail, allowing for a detailed review. However, it is unlikely that each of the abstractions will have the same risk significance. The staff will review the abstractions according to their risk significance determined in the multiple barrier review. Nevertheless, until the DOE completes its safety case and the license application, the model abstraction sections of this document must remain flexible and have sufficient detail.

Important to performance means important to meeting the overall performance objective specified in proposed 10 CFR Part 63.113, which is a radiation exposure limit. The risk of radiation health effects is the basis for the radiation exposure limit. The staff will focus its review to ensure the degree of technical support for models and data abstractions is appropriate for the associated contribution to risk. This means the staff will review each model abstraction commensurate with the degree the DOE relies on the abstraction to prove its safety case. The staff will be familiar with the DOE safety case because of the multiple barrier review.

## 3.0 IMPORTANCE OF ISSUE AND SUBISSUES TO EVALUATION OF REPOSITORY PERFORMANCE

As noted in Chapter 2.0, DOE's demonstration of compliance with applicable standards for disposal of HLW in a geologic repository at Yucca Mountain will need to meet the performance objectives in the implementing regulations. Because the proposed HLW repository at the YM site is a unique facility with a long compliance period, demonstration of compliance with a dose standard is expected to be a complex and difficult task. The TSPA must be sufficiently robust, comprehensive, transparent, and traceable such that the Commission can find with reasonable assurance that the performance objectives are met and public health and safety are protected.

### 3.1 ROLE OF PERFORMANCE ASSESSMENT IN THE U.S. NUCLEAR REGULATORY COMMISSION HIGH-LEVEL WASTE PROGRAM

At the current time, the proposed regulations for the YM site requires DOE to provide a comprehensive PA in its license application (U.S. Nuclear Regulatory Commission, 1999a). NRC will ensure in its review of an LA that the proposed repository will adequately protect public health and safety. As part of its review process, NRC staff will evaluate not only the basis for DOE's models and parameters (e.g., field, laboratory, and natural analog data), but will perform independent analyses to check selected portions of DOE performance assessment. It will be necessary, therefore, for NRC to select those portions of DOE's assessment requiring independent verification through more detailed quantitative analyses and limited laboratory and field studies. This selection will be risk informed, that is, those aspects contributing greater risk (or limiting risk more greatly) will be investigated in greater detail.

NRC used TSPA activities in prelicensing technical exchanges to begin this prioritization process with DOE. Specifically, in its 1989 Site Characterization Analysis (SCA) (U.S. Nuclear Regulatory Commission, 1989), NRC staff commented on DOE's Site Characterization Plan (SCP) (U.S. Department of Energy, 1988), as required under the NWPA, and highlighted the need for TSPAs early in the site characterization program (U.S. Nuclear Regulatory Commission, 1989). The staff expressed concern that DOE needed to improve the technical integration of its site characterization program and emphasized the important role that PA should play to integrate data-gathering activities and to guide evaluations of those data. TSPA activities also supported NRC staff interactions with EPA and NAS as a part of the NAS reevaluation of EPA's HLW standards, as they apply to a proposed repository at YM.

NRC staff will continue to rely on its TSPA activities to (i) support ongoing interactions, (ii) evaluate DOE's TSPA to support SR (TSPA-SR) and provide a basis for NRC's sufficiency comments, (iii) facilitate constructive review and comment on DOE's Draft Environmental Impact Statement, and (iv) prepare for an effective and efficient review of a potential LA.

### 3.2 IMPORTANCE OF SUBISSUES TO TOTAL SYSTEM PERFORMANCE

The four subissues identified in Chapter 2.0 include the essential components of a TSPA and the use of the TSPA to demonstrate compliance with regulatory requirements. Resolution of Subissue 1, System Description and Demonstration of Multiple Barriers, ensures that DOE has: (i) identified the design features of the EBS and natural features of the geologic setting considered to be important barriers to waste isolation, (ii) described the capability of the barriers important to waste isolation, and (iii) provided a technical basis to describe the capability of the barriers. Furthermore, resolution of Subissue 1 ensures that compliance calculations in DOE's TSPAs are clear and consistent; clear and consistent calculations build confidence in the overall analysis and allow the staff to efficiently complete its independent review. Resolution of Subissue 2, Scenario Analysis, ensures that the PA appropriately considers likely processes and events in the PA. Resolution of Subissue 3, Model Abstraction, ensures that the assumptions, conceptual approaches, data, models, and abstractions used in DOE's TSPAs are appropriately integrated and technically defensible. Resolution of Subissue 4, Demonstration of the Overall Performance Objective, ensures that DOE appropriately executed the PA to demonstrate that repository performance for a range of FEPs will meet the overall performance objective (i.e., expected annual dose to the average member of the critical group).

## 4.0 TECHNICAL BASES FOR REVIEW

This chapter describes a process that NRC staff will follow in reviewing DOE's TSPAs and also provides a path to issue resolution. This chapter also describes the process that NRC staff will use to evaluate DOE's demonstration of compliance with the overall performance objective and requirements for multiple barriers. As mentioned before, acceptance criteria and review methods will be provided in the YMRP. Technical bases are specified for each of the subissues identified in Chapter 2.0. Past independent research by the staff, information in open literature, review of previous DOE TSPAs, information learned during meetings with DOE, the approach used in the TPA Version 3.2 (Mohanty and McCartin, 1998) code; acceptance criteria and review methods in the YMRP, and technical bases contained in the IRSRs of other KTIs have been considered in formulating this chapter. In addition, insight gained from sensitivity studies using the TPA Version 3.2 code has been incorporated to the extent feasible.

Two programmatic acceptance criteria, quality assurance (QA) and expert elicitation, are applicable to all the TSPAI subissues, but apply directly in the case of subissues two and three (scenario analysis and model abstraction subissues), where the adequacy and quality of data, models, and computer codes are evaluated. The development of data, models, and computer codes—whether they are used for scenario analysis to support development of conceptual models in the PA, or provide input to the PA—should satisfy the acceptance criterion on QA. Similarly, the use of expert elicitation should satisfy the appropriate acceptance criterion. Specific criteria and review methods can be found in Revision 1 of the YMRP.

## 4.1 SYSTEM DESCRIPTION AND DEMONSTRATION OF MULTIPLE BARRIERS

### 4.1.1 Transparency and Traceability of the Analysis

In determining whether DOE has demonstrated compliance with applicable regulatory criteria, the NRC staff, using acceptance criteria identified in the YMRP, will review DOE's TSPA. Transparency and traceability of the analysis requires a description that allows for an adequate understanding of DOE's approach. In addition, a transparent and traceable PA facilitates the interpretation of the results of the performance assessment.

Transparency has been defined by the Nuclear Energy Agency (NEA) as an attribute of a PA report "written in such a way that its readers can gain a clear picture, to their satisfaction, of what has been done, what the results are, and why the results are as they are." (Nuclear Energy Agency, 1998) In broader terms, transparency will allow the NRC staff to clearly identify ways to test the accuracy and reproducibility of DOE's results to ensure that the DOE meets the normal requirements for technical explanations, proof of authenticity, and legitimacy of actions.

Traceability enhances transparency. Traceability exists when there is an unbroken chain linking the result of an assessment (e.g., final dose calculation) with models, assumptions, expert opinions, and data used in the formulation of the result (National Conference of Standards Laboratories, 1994). The NEA has defined traceability as an attribute of an assessment or selected portions of an assessment that includes an unambiguous and complete record of the decisions and assumptions made, and of the models and data used in arriving at a given result (Nuclear Energy Agency, 1998).

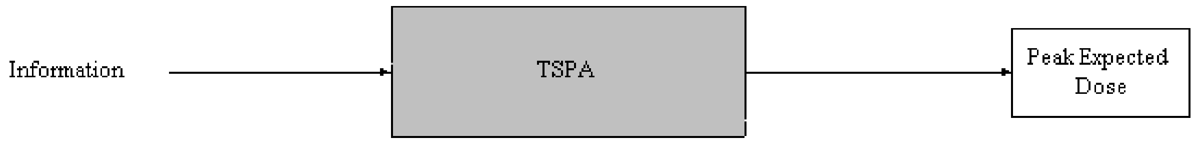
During the license review process, the NRC staff will review DOE's TSPA for completeness (e.g., inclusion of FEPs that could significantly influence the performance measure) and accuracy. Without transparency and traceability, DOE's TSPA may be difficult to understand to even a well-trained technical expert, and appear as no more than a "black box" from which estimates of repository performance are produced. Information (e.g., FEPs and laboratory data) flows into the TSPA and results are produced, but it may not be clear how the results were generated [see Figure 1(a)]. As the degree of transparency and traceability increase, the processes within the TSPA become apparent [see Figure 1(b)]. For DOE's TSPA to be sufficiently transparent and traceable for reproducibility, the assumptions, uncertainties, rationale, and data used in the TSPA must all be visible. For the TSPA to be traceable, all steps in the development of the TSPA must be traceable, including the following: (i) decisions taken in the repository design; (ii) decisions to exclude or include certain FEPs; and (iii) demonstration that the conceptual and detailed numerical approach is adequate for the purpose at hand (e.g., demonstrate that additional sophistication will not substantially alter modeling results or that the model abstraction is bounding) [see Figure 1(c)].

Transparency and traceability is further complicated in that the degree of transparency of a document, model, code, or methodology to a particular reader will vary by the technical background of the reader (Nuclear Energy Agency, 1998). It is recognized that it is neither possible for all stakeholders (e.g., public, environmental groups, state government, the NRC) to understand all technical issues in detail nor is it possible for all experts to understand each other's disciplines in detail (Swedish Nuclear Power Inspectorate, 1998). However, the DOE must provide sufficient transparency and traceability to convince the NRC that compliance with regulatory criteria will be achieved. The acceptance criteria for transparency and traceability addresses theTSPA documentation style, structure, and organization; The acceptance criteria for transparency and traceability are specifically applied to the documentation for (i) FEPs identification and screening; (ii) model abstraction methodology; (iii) data use and validity; (iv) assessment results; and (v) code design and data flow. With this revision (Revision 3), the acceptance criteria and review methods have been moved to the YMRP. Only the technical basis for this subissue are presented next.

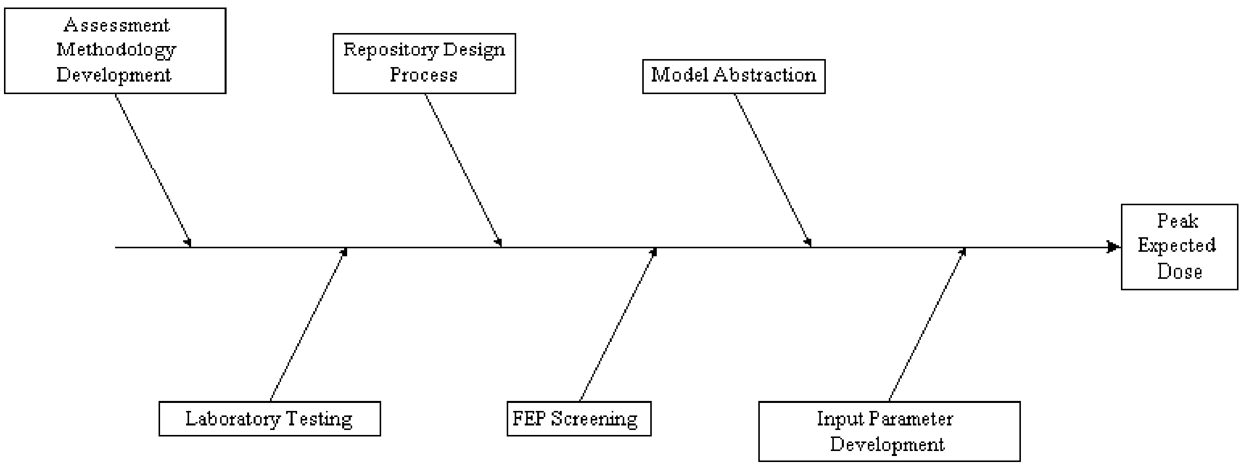
#### 4.1.1.1 Total System Performance Assessment Documentation Style, Structure, and Organization

The complexity of DOE's TSPA may not permit a simple trace from data sources through the TSPA models to results. TSPA information may be distributed over numerous documents and there may be parallel trails for different technical areas. In addition, there may be interactions between various trails and additional assumptions and decisions invoked along each trail. TSPA information may also be stored electronically in word processor files and databases. For the NRC staff to review the information recorded in the many documents and data sources, traceability and transparency require that source documents be well structured and organized. Transparency and traceability will apply to documentation pertaining to all subissues.

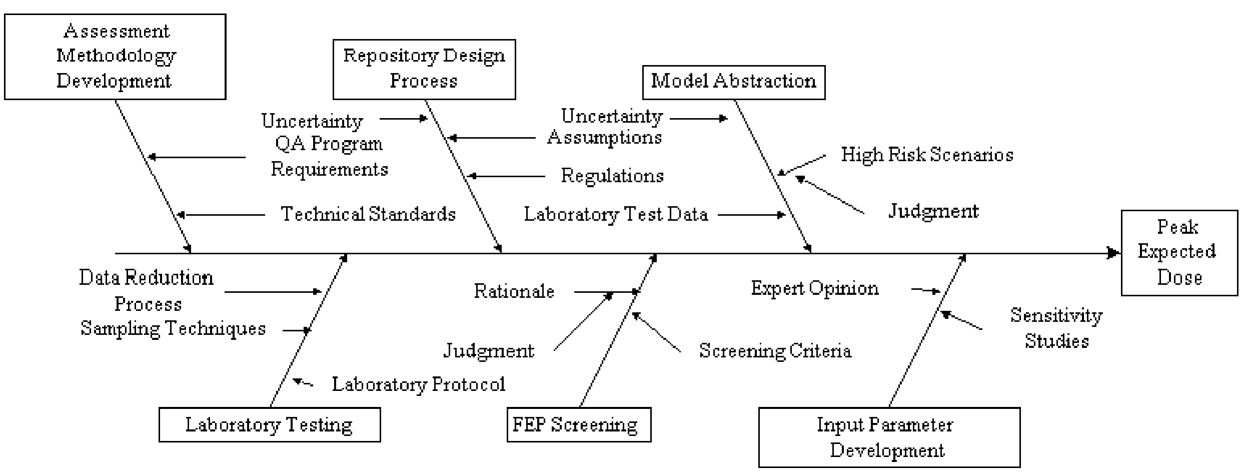
TSPA documentation must be structured to facilitate in-depth reviews so the NRC staff can probe the documentation and do independent evaluations of the DOE analyses. Additionally, all stakeholders will scrutinize DOE documentation. If a reviewer has to search multiple documents to address a specific issue of interest, accurate mapping between volumes (e.g., cross-reference matrices) should be provided. As one measure of transparency, the best documents are succinct, use appropriate terminology, and use an appropriate number of figures and diagrams. Documentation must balance the level of detail, clearly state




(a)




(b)




(c)

**Figure 1. Illustration of degrees of transparency in the U.S. Department of Energy's Total System Performance Assessment: (a) black box, (b) partially transparent, and (c) transparent**

assumptions and simplifications made, and reference the source of basis data (e.g., dose conversion factors) in main volumes (Swedish Nuclear Power Inspectorate, 1997).

#### 4.1.1.1.1 Features, Events, and Processes Identification and Screening

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 those FEPs that are sufficiently likely to occur within the compliance period have been adequately identified and addressed. Transparency and traceability in the FEPs identification and screening will be evaluated in the Scenario Analysis section of this IRSR (Section 5.2).

The staff will review categorization of FEPs during evaluation of DOE's scenario analysis process [see Section 5.2]. The documentation of the relationships between FEPs (e.g., corrosion of the WP or whether rockfall will fail the package) is necessary to support modeling decisions. Documentation of all steps in a FEPs screening methodology is necessary to ensure that DOE has properly considered relevant FEPs associated with the future evolution of the repository and has provided the traceability needed to facilitate future revisions.

#### 4.1.1.1.2 Model Abstraction Methodology

Transparency and traceability should be sufficient to provide an adequate understanding of the mathematical framework for the conceptual models (i.e., abstraction) and assess the repository performance. Specifically, the documentation must identify the relationship of the site information and the actual repository design to the assumptions, models, and parameters used in the PA calculations. Transparency and traceability of DOE's model abstraction methodology will be evaluated in the Model Abstraction section of this IRSR (Section 5.3).

The DOE has developed data used in the TSPA to describe different physical and chemical aspects of the repository, the geology and geometry of the surrounding area, and possible scenarios for human intrusion. Data may be well-established physical constants or may be physical, chemical or geologic characteristics measured or inferred from experimentation and observation. The source and validity of these values and their use in the assessment must be transparent and traceable. The transparency and traceability of DOE's use of data and demonstration of the validity of these data will be evaluated in the Model Abstraction section of this IRSR (Section 5.3).

#### 4.1.1.1.3 Assessment Results

DOE is expected to support demonstration of compliance with the overall performance objective with a TSPA. To be transparent, DOE's TSPA should contain an evaluation of performance of the YM repository relative to compliance with the individual dose limit and an explanation of how the estimated performance was achieved. Explanation of how the estimated performance was achieved should reveal an understanding of the relationship between the performance of individual components or sub-systems of the repository and the total system performance.

Transparency and traceability should be sufficient to allow for an adequate understanding of the results of DOE's TSPA. The DOE is required to demonstrate that the geologic repository can meet the overall performance objective, is resilient against human intrusion, and consists of multiple barriers. Demonstration that all these requirements have been met should include performance results traceable to decisions regarding data, models, and computer codes. The transparency and traceability of DOE's assessment results will be evaluated in the Demonstration of the Overall Performance Objective section of this IRSR (Section 5.4).

Demonstration of compliance with the overall performance objective requires more than simply presenting the peak expected annual dose calculated by the TSPA. Enough information should be presented for reviewers to be able to understand why the results came out as they did. It should be clear which assumptions and subsystems are driving system performance so that staff can focus their review in these areas. Intermediate outputs should be presented so that reviewers can understand how subsystems are influencing performance. Additionally, the DOE should identify parameter combinations that may lead to relatively high consequences so staff can determine the likelihood of the conditions leading to these results actually occurring within the repository system.

The DOE will be required to demonstrate that the geologic repository is composed of multiple barriers and the NRC staff will confirm these barriers consist of major repository subsystems and components of distinct and diverse features, characteristics, or attributes. Although numerical criteria have not been specified for individual barriers, presentation of intermediate results for individual barriers will help the staff to build an understanding of the behavior of the total system (Nuclear Energy Agency, 1998).

#### 4.1.1.1.4 Code Design and Data Flow

Because of the overall complexity of the YM system and the need to understand the total system behavior, abstracted models are expected to make up an integral part of DOE's TSPA. It is important that the DOE TSPA code design and data flow be transparent because the NRC will need to review the code to enhance staff understanding of TSPA methodology and results. The transparency and traceability of DOE's code design and data flow will be evaluated in the following sections of this IRSR: System Description and Demonstration of Multiple Barriers (Section 5.1), Model Abstraction (Section 5.3), and Demonstration of the Overall Performance Objective (Section 5.4).

A fundamental principle of structured design is that a large or complex system such as the DOE's TSPA code must be partitioned into manageable modules to be transparent. However, it is important that this partitioning of the system be carried out in such a way that the modules are as independent as possible–modular. Transparency and traceability of DOE's TSPA should allow for an adequate understanding of the design of the code (e.g., computational scheme), including the flow of information (input and output) between the various modules and within a module. Without transparency and traceability, the TSPA code will appear as a series of black boxes [see Figure 2(a)]. For the TSPA code to be sufficiently transparent and traceable, the coupling between modules and internal structure of the modules must be visible [see Figure 2(b)].

### 4.1.2 Demonstration of Multiple Barriers

Proposed 10 CFR Part 63 (U.S. Nuclear Regulatory Commission, 1999a) includes a requirement that the repository system be composed of multiple barriers. In demonstrating compliance with the multiple barrier requirement, DOE would need to evaluate and discuss, including uncertainty of, the effectiveness and diversity of the barriers as a measure of the resiliency of the repository. Demonstration of multiple barriers will be supported with DOE's PA, which includes model abstraction (Section 4.3), treatment of scenarios (Section 4.2), and transparency of the analysis (Section 4.1.1).

The following steps are based on meeting the requirements at draft 10 CFR 63.113(a), (d) and 10 CFR 63.114(b)(1)–(4).

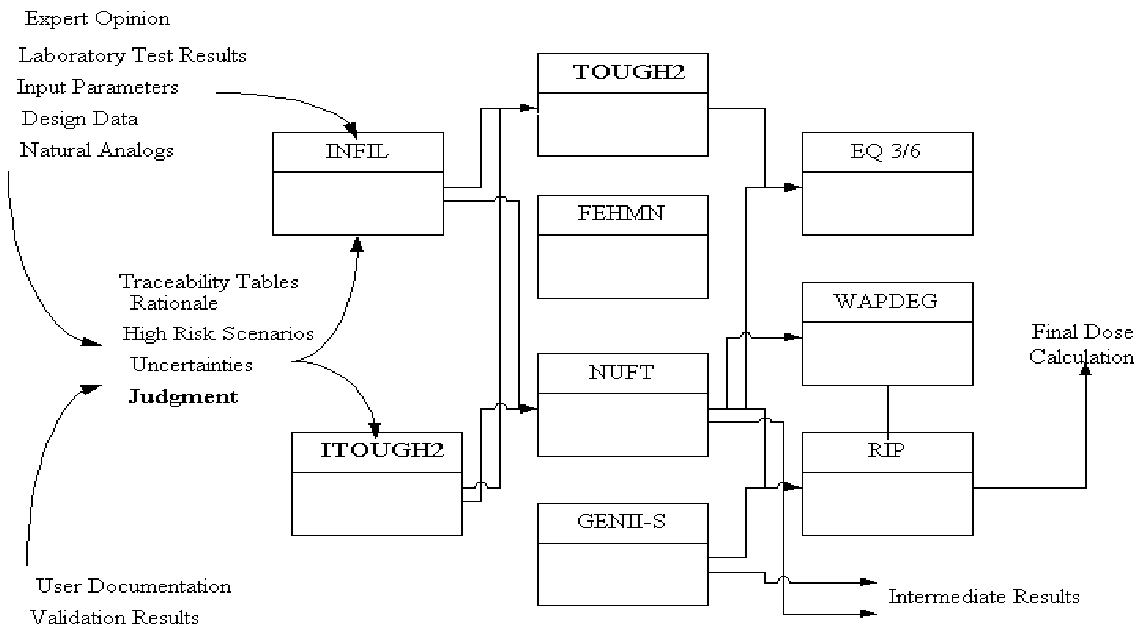
#### 4.1.2.1 Identification of Barriers

In general terms, performance assessment quantifies the safety of a waste repository by estimating the nature and probability of radionuclide releases to the environment and the potential impacts on public health and safety and the environment. Those attributes of the repository system (both natural and engineered) that contribute to the isolation of radioactive waste are considered barriers. An identification of the barriers important to waste isolation is fundamental to the description of DOE's safety case. To meet the requirements for multiple barriers in 10 CFR 63.113 and 63.114, DOE must identify those barriers that contribute significantly to repository performance so NRC staff can focus its review on those parts of the repository system. Also to meet the requirements of 10 CFR 63.113(a), DOE must identify at least one natural barrier and one engineered barrier.

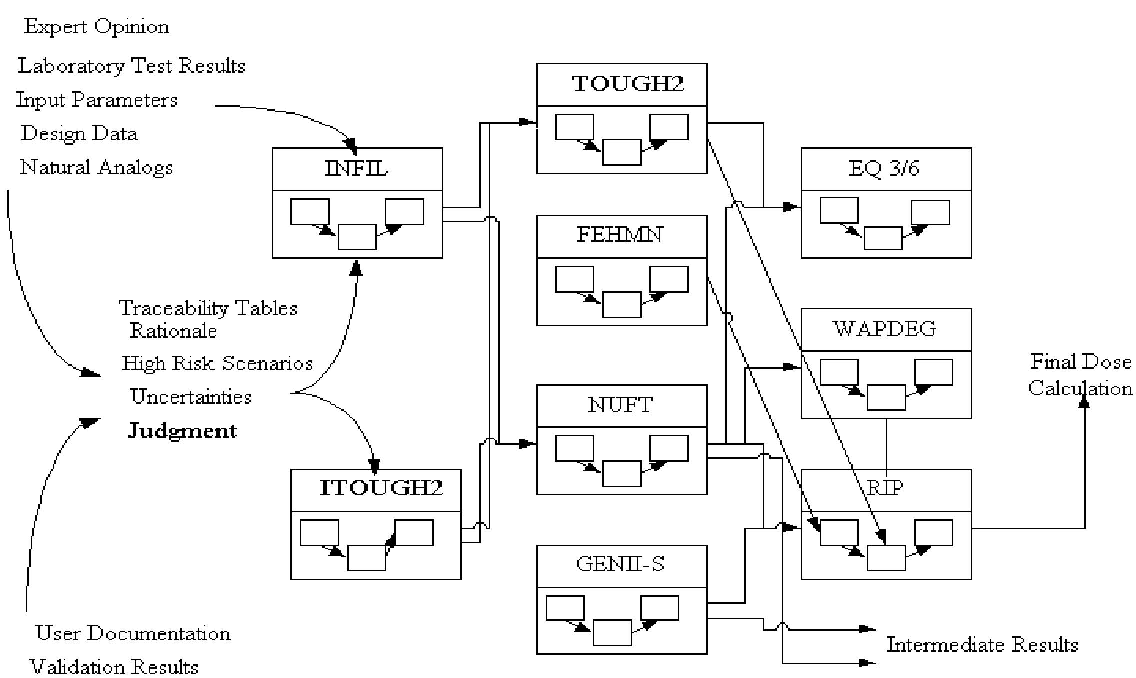
Geologic disposal of HLW is predicated on the expectation that a portion of the geologic setting will act as a barrier, to water reaching the waste and to dissolved radionuclides migrating away from the repository, and, thus, contribute to the isolation of radioactive waste. Although there exists an extensive geologic record ranging from thousands to millions of years, this record is subject to interpretation and includes many uncertainties. Most of these uncertainties can be quantified generally and are addressed by requiring the use of a multiple-barrier approach. Specifically, an engineered barrier system, consisting of one or more distinct engineered barriers, is required in addition to the natural barriers implicit in a geologic setting. Similarly, although the composition and configuration of engineered structures, as well as their capacity to function as barriers, can be defined with a degree of precision not possible for natural barriers, it is recognized that, except for a few archaeologic analogs, there is no experience base for the performance of complex, engineered structures during periods longer than a few hundred years. It is expected that DOE will demonstrate that the natural barriers and the EBS will work in combination to enhance overall performance of the geologic repository (U.S. Nuclear Regulatory Commission, 1999a).

#### 4.1.2.2 Description of Barrier Capability

DOE must evaluate the behavior of barriers important to waste isolation in the context of the performance of the geologic repository. DOE could select from a variety of methods to demonstrate the capability of barriers to isolate waste. Regardless of the method and the level of quantification, it is expected that the capability of individual barriers to perform their intended function and the relationship of that function to limiting radiological exposure would be described. Acceptable methods for demonstrating compliance with the multiple barrier requirement could include, but not necessarily be limited to, performing sensitivity analyses, modeling the behavior of individual barriers, quantifying how individual barriers contribute to




(a)




(b)

**Figure 2. Illustration of degrees of transparency in the U.S. Department of Energy's Total System Performance Assessment code: (a) partially transparent and (b) transparent**

performance, and delineating the capabilities of the barriers to isolate waste. DOE has flexibility in selecting the methods to demonstrate the waste isolation capability of the multiple barriers that must compose its repository design, but DOE must demonstrate that the repository system is composed of multiple barriers. DOE must also demonstrate an understanding of the resiliency of the geologic repository provided by the barriers important to waste isolation to ensure defense-in-depth and increase confidence that the postclosure performance objective will be achieved (U.S. Nuclear Regulatory Commission, 1999a).

#### 4.1.2.3 Technical Basis for Barriers Identified as Important to Performance

The technical basis for the capability of barriers is a key aspect to the demonstration that the repository can meet the performance objectives in 10 CFR Part 63. Those systems relied on most for the performance of the repository system will require the strongest technical basis to defend the amount of credit taken for their presence. Field, laboratory, and natural analog data provide a strong basis on which models in the TSPA should be based. If adequate data are not available or readily attainable, other information, such as expert elicitation, may be used as a basis for TSPA models. If conservative assumptions are used to bound the behavior of a subsystem, little technical basis is needed to defend this model, other than to demonstrate that the model of the subsystem performance is actually conservative.

## 4.2 TOTAL SYSTEM PERFORMANCE ASSESSMENT METHODOLOGY: SCENARIO ANALYSIS

An important element of a TSPA for a geologic repository for HLW is an evaluation of repository safety considering potential future conditions to which a repository may be subjected during the period of regulatory concern. Such an evaluation may be accomplished through scenario analysis. Scenario analysis addresses those processes and events necessary to describe what can reasonably happen to the repository system. Because there are many possible ways in which the geologic repository environment can evolve, the goal of scenario analysis is to evaluate repository performance for a sufficient number of these possible evolutions to support a defensible representation of performance.

There are generally two approaches available for analysis of uncertainty in scenario definition. Uncertainties can be treated/analyzed in geologic repository performance by (i) incorporating variability in parameters directly into the model(s) and data (bases) used to describe the repository systems and (ii) approximating the alternative ways in which the repository system might perform in the future, through the use of scenarios.[1] Most uncertainty analyses use a combination of these two approaches.[2] The approaches are not mutually exclusive and both may be used in the analysis to treat different types of uncertainty.

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[1]Not all HLW programs in the world define scenarios in exactly the same way [see Organization for Economic Cooperation and Development/Nuclear Energy Agency–OECD/NEA (1992); and Stenhouse, et al. (1993)]. However, a strict definition of a scenario is not critical for this section, except to note that each scenario has a conceptual model associated with it.

[2]See OECD/NEA (1986), Stenhouse, et al. (1993), Thompson and Sagar (1993), and Bonano and Baca (1994) for a review of various scenario analysis methods.

The discrete plausible future evolution of the repository system during the period of regulatory concern is called a scenario. A scenario includes: (i) a postulated sequence of events (or may be characterized by the absence of events) and (ii) assumptions about initial and boundary conditions. Because there is inherent uncertainty in both the repository system and processes and events that can effect the repository system, many different evolutions are possible. The proposed YM-specific EPA standard and the NRC implementing regulations specify a quantitative overall total system performance criterion in terms of individual dose to the average member of a critical group. The demonstration of compliance is expected to require a probabilistic assessment of repository performance, which would include the consideration of multiple scenarios. A probabilistic approach in which scenario classes[3] are assigned probabilities and the consequences weighted according to these probabilities is used by NRC (Wescott, et al., 1995). NRC will use its approach (see also Cranwell, et al., 1990) to evaluate DOE's scenario analysis, so this approach forms the structure for the NRC review methods and undergirds the technical bases that follow.

DOE's PA will be evaluated to determine if DOE has adequately identified and addressed those processes and events that are sufficiently likely to occur within the compliance period. The acceptance criteria for scenario analysis address: (i) identification of an initial list of processes and events; (ii) classification of processes and events; (iii) screening this initial list of processes and events; (iv) formation of scenario classes using the reduced set of processes and events; and (v) screening scenario classes. Models of processes and events included within the PA will be evaluated against the model abstraction acceptance criteria. Steps (i) to (iii) apply to the screening of processes and events from the PA on a general level; those processes and events that are not excluded from the PA will need to be addressed either through consequence models or through the definition of scenarios. The application of scenarios to the demonstration of compliance with the overall performance objective and multiple barriers will be addressed under those subissues.

### 4.2.1 Identification of an Initial Set of Processes and Events

As stated earlier, several methods have been proposed for the identification of the set of scenarios for inclusion in the TSPA. It has been reported that DOE is using the method of event trees for identifying scenarios for the proposed repository at YM (Barr and Dunn, 1993).

In DOE's application of the event tree approach, a causative event is postulated to occur and its effect is traced through binary branches. A fault tree approach has also been suggested. In this approach, the tree is constructed from the top down, starting with the undesirable end effect. Unless carefully implemented, the fault tree approach may miss some credible scenarios. The logic tree approach, which allows for more than two branches at a node of the tree, has been used by the Electric Power Research Institute (EPRI) (see Kessler and McGuire, 1996). Based on the work by Cranwell, et al. (1990), the NRC developed a Latin Square method of evaluating repository performance using scenario classes, which are characterized by the presence or absence of particular processes and events.

[3]In the NRC approach, scenario classes are formed as combinations of event classes. Event classes consist of a set of scenarios that share the occurrence of fundamentally similar processes and events (e.g., the set of all igneous events or the set of all faulting events). A scenario class could consist of those scenarios that include the occurrence of both an igneous event and a faulting event during the compliance period.

An event[4] is an occurrence at a discrete location in space and during a specific interval of time. Examples for the YM site include igneous events (e.g., a dike intrusion or the formation of a vent) and tectonic events (e.g., the formation of new faults, slip on existing or new faults, and seismic events). These events may cause new geologic features to be formed (e.g., new faults and volcanic cones) or new processes to be activated (e.g., magmatic flow) that may have to be considered in the PA. Generally, the behavior of the components within the system boundary (e.g., degradation of WPs, flow through fractures, propagation of thermal pulse, and gravity refluxing of pore water) is modeled as a response to processes and events acting on the repository system. A comprehensive list of processes and events needs to be identified to demonstrate that sufficiently likely processes and events have been considered in the analysis.

### 4.2.2 Classification of Processes and Events

After a comprehensive list of processes and events has been established, processes and events may be grouped into categories.[5] This categorization is used to support the evaluation of the completeness of the list of identified processes and events. It also facilitates the screening of processes and events, based on their credibility or likelihood (see Section 4.2.3). These categories of processes and events may be combined to form scenarios (see Section 4.2.4). Combinations of processes and events may also be screened from the analysis (see Section 4.2.5).

DOE has flexibility in how it categorizes processes and events, however the breadth of categories must be defendable (considering uncertainty). The categorization of processes and events also needs to be well documented to provide transparency and traceability. All processes and events included in DOE's comprehensive list must be assigned to at least one category. Categories that are defined narrowly might not be appropriate for screening processes or events from the PA. Undefendable, narrowly-defined categories of processes and events that result in screening of processes or events from the PA are unacceptable, because they result in an incomplete assessment of repository performance.

NRC uses a Latin Square approach to categorizing processes and events. This approach is useful for evaluating completeness. In the NRC Latin Square approach, a finite set of event classes[6] is defined, where each event class contains fundamentally similar events, which differ only in detailed characteristics. For example, the set of all igneous events (say **I**) may form an event class, the set of all fault-related movement (say **F**) events may form another, and the set of seismic events (say **S**) a third. In this approach, event classes also are used to represent the absence of a processes or events. For example, igneous events may occur (i.e., **I**) or they may not (i.e., $\bar{\mathbf{I}}$). These broad categories can be used to estimate the probability that any one of a

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[4]In scenario analysis, events are not treated individually, so probabilities are assigned to groups of similar events that differ only in their attributes (e.g., time of occurrence or magnitude).

[5]Several different categorization schemes are possible for events and processes (see Cranwell, et al., 1990 or Wescott, et al., 1995). However, probabilities of fundamentally similar processes and events are used to exclude general categories of processes or events from the PA based on the probability of their occurrence.

[6]"Event classes" refers to the categories of processes and events used by NRC in its Latin Square approach to scenario analysis.

related set of events could occur during the period of regulatory concern, where the probability can be used to screen unlikely events from the PA. The event classes also can be used as the basis for forming scenario classes.

### 4.2.3 Screening of Processes and Events

A screening process is followed to exclude from further consideration those categories of processes and events that are not credible or are not sufficiently likely to warrant inclusion in the PA. Categories of processes and events that are sufficiently likely to be included in the PA may be omitted from the PA, if their omission would not significantly change the calculated expected annual dose.

Estimating probabilities of processes and events is a particularly difficult aspect of scenario development. Relevant site and regional data, along with data from analog regions, should be used to assign probabilities of occurrence to processes and events. However, there are several methods to develop these probabilities and different scientific interpretations of data can lead to different estimates (e.g., see Hunter and Mann, 1992). The approach used to form the categories could influence whether processes and events are screened from the calculation. It is important that defendable (typically broad) categories are used during the screening of processes and events on the basis of their probability of occurrence. The use of broad (or fundamental) categories minimizes the potential for important events being screened from further consideration on the basis of how they were categorized. For example, partitioning Igneous Activity (IA) into categories that include details of its attributes (e.g., intrusive igneous events with dike lengths of 2 km or less) could, inappropriately, result in the screening of each category of igneous activity from the PA. Even if it may be reasonable that the occurrence of an event is random with space or time or some other characteristic, categories cannot be narrowed through the use of assumptions unless those assumptions are supported by data.

In the NRC Latin Square approach, each event class contains fundamentally similar events, which differ only in detailed characteristics. Probabilities are determined for the event classes where there is an occurrence of the process or event (e.g., **I**). The sum of related event class probabilities, where the process or event either occurs or is absent (e.g., **I** and **I**$^-$; **F** and **F**$^-$; and **S** and **S**$^-$), must equal one. This property is used to calculate the probability of event classes defined by the absence of a process or event occurring. Probabilities are assigned to event classes, whereas variability in the attributes of processes and events (e.g., time of occurrence, location, duration, amount of energy released, rates of propagation of disturbance) are treated through parameter distributions as part of model abstraction. In the NRC approach, event classes are defined broadly to avoid eliminating potentially important processes and events from the analysis (e.g., fault displacement occurring within the period of regulatory interest). Narrowly defined categories of processes and events that are not defensible result in the inappropriate screening of processes or events from the PA.

Processes and events that cannot be screened on the basis of probability, may still be omitted from the PA. It is possible to exclude from the PA those processes and events that do not significantly change the calculated expected annual dose. In the event of a robust repository design that results in small doses to the average member of the critical group, the staff is interested in processes and events that could significantly change the margin between the calculated expected annual dose and the regulatory requirement. Detailed calculations of the consequences is not required for screening purposes. The use of representative or conservative estimates of consequences may be used to support excluding processes and events from the PA; these estimates should consider, as appropriate, conditions that would increase the potential for the process or event to make a significant contributions to the expected annual dose. The amount of information required to support excluding categories of processes and events from the PA may vary from one category to another, based on the processes and events involved.

### 4.2.4 Formation of Scenarios

The processes and events remaining after screening can either be included through model abstraction or incorporated into scenarios. Combinations of categories of processes and events that remain after screening and are not addressed through model abstraction form scenario classes. Scenario classes may be used to screen some combinations of processes and events from the PA (see Section 4.2.5).

Processes and events that remain after screening can be addressed either through model abstraction or incorporated into scenarios. A decision will have to be made for each process and event. NRC uses a Latin Square approach based on event classes, where each event class contains fundamentally similar events, which differ only in detailed characteristics. These event classes are used to address processes and events that can act on the repository system, resulting in new features (e.g., new faults, volcanic cones) or new processes (e.g., magmatic flow) that may have to be considered in the PA. The response of the repository to these events is addressed through model abstraction. This results in event classes such as faulting ($\mathbf{F}$ and $\mathbf{F}^-$), seismicity ($\mathbf{S}$ and $\mathbf{S}^-$), and igneous activity ($\mathbf{I}$ and $\mathbf{I}^-$). These event classes can be combined into scenario classes such as $\mathbf{FSI}$, $\mathbf{FSI}^-$, $\mathbf{FS}^-\mathbf{I}$, $\mathbf{FS}^-\mathbf{I}^-$, $\mathbf{F}^-\mathbf{SI}$, $\mathbf{F}^-\mathbf{SI}^-$, $\mathbf{F}^-\mathbf{S}^-\mathbf{I}$, and $\mathbf{F}^-\mathbf{S}^-\mathbf{I}^-$. The Latin Square approach provides a complete set of scenario classes and ensures that the scenario classes are mutually exclusive. Scenario classes are broadly defined and distinct, which is useful for screening scenario classes. This formulation of scenario classes does not make a distinction between different event sequences, which requires that differences in consequences associated with the timing of events has to be addressed through model abstraction. Caution is needed in defining scenario classes to ensure that the definition of the scenario class does not result in the inappropriate screening of the scenario class from the PA.

### 4.2.5 Screening of Scenario Classes

Categories of processes and events may be combined into scenario classes. Scenario classes may be omitted from the PA if: (i) they are not credible, (ii) they are not sufficiently likely to warrant inclusion in the PA, or (iii) their omission would not significantly change the calculated expected annual dose.

The NRC method and the approach believed to be used by DOE to screen scenario classes are very similar. After screening is performed on processes and events, processes and events that remain are addressed either through model abstraction or scenario analysis. Those processes and events that are being addressed through scenario analysis are combined to form a comprehensive set of scenario classes. A complete set of scenario classes is needed to fully analyze the range of possible evolutions for the repository. However, it is not necessary that every scenario class needs to be analyzed through the PA. Scenario classes with very low probabilities of occurring during the period of regulatory concern do not need to be considered in the PA. Scenario classes that are not credible should not be included in the PA. Credible scenario classes may be omitted from the analysis, if they have a sufficiently low probability. This is analogous to the screening that is used for categories of processes and events, however, this screening is performed on combinations of processes and events. In the event of a robust repository design that results in very small doses to the average member of the critical group, the staff is interested in combinations of processes and events that could significantly change the margin between the calculated expected annual dose and the regulatory requirement. There is a risk that scenario classes may be narrowly defined, resulting in low probabilities (or a small contribution to the expected annual dose) and the screening of potentially important processes. It is unlikely that narrow definition of scenario classes will be supported by the available information, because by definition the events are very infrequent if they are close to the screening criteria (1E-8 /yr). Therefore, screening on the basis of probability may be limited to combinations of initiating processes and events. This limitation makes a delineation between processes and events that act on the repository and those that represent the response of the repository. NRC, for example, forms scenario classes exclusively from initiating events (e.g., fault displacement, seismicity, volcanism).

The level of categorization of processes and events needs to be defendable. If screening is based on consequences (i.e., contribution to the calculated performance measure), the breadth of a category would not be important if the performance measure is not impacted. Approaches, such as event tree, fault tree, or logic tree would be implemented using different classification schemes. Processes and events may make significant contributions to the expected annual dose only under certain conditions or for specific attributes of the process or event. It is possible to exclude from the PA those combinations of processes and events that do not significantly change the calculated expected annual dose. A narrowly defined scenario class might be screened, based on its small contribution to the expected annual dose, if it is evaluated in isolation. Therefore, it may be necessary to evaluate the definition of related scenario classes to evaluate whether they have been properly screened from the analysis. Although categories may be screened individually, the cumulative effect of omitting processes and events could become significant and needs to be considered.

The amount of information required to support excluding categories of processes and events from the PA may vary from one category to another, based on the processes and events involved. The effect of screening processes and events on the calculation of the performance measure has to be considered, when screening on the basis of consequences is applied. The probabilities assigned to categories of processes and events will have to be adjusted after categories have been screened to assure consistency with the principles of probability calculus.

The NRC approach to scenarios uses the Latin Square method, which uses the specification of event classes (e.g., faulting, IA, and seismicity). Probabilities for the occurrence of these processes can be estimated using data from site characterization. Probabilities for the absence of these processes during the compliance period can be found, because the sum of the probability that the process occurs or is absent (e.g., $\mathbf{F}$ and $\mathbf{F}^{-}$) must equal one. The NRC approach is demonstrated using a simple example, where event classes associated with the independent processes $\boldsymbol{\Theta}$ and $\boldsymbol{\Psi}$ are used to form scenario classes. The assumption of independence simplifies the example, but may not be appropriate for all combinations of event classes.

The following probabilities for the two event classes will be assumed in this illustration of the Latin Square method: **Θ** (P = 0.9) and **Ψ** (P = 0.05); where the probabilities are for the processes or events within the event class either being present or occurring within 10,000 years. Each of these event classes has a probability greater than $10^{-4}$, so they may not be screened on the basis of probability. The probability of **Θ** or **Ψ** not being present or not occurring within 10,000 years can be found using the principles of probability; that is $\mathbf{\Theta^-}$ (P = 0.1) and $\mathbf{\Psi^-}$ (P = 0.95). These event classes can be combined to form scenario classes (e.g., **ΘΨ**, $\mathbf{\Theta\Psi^-}$, $\mathbf{\Theta^-\Psi}$,$\mathbf{\Theta^-\Psi^-}$). Because these event classes are independent, the probability of each scenario class equals the product of its constituent event classes. Screening criteria may be applied to the four scenario classes to determine if any of the scenario classes might be omitted from the calculation. Table 2 illustrates the use of the Latin Square to form scenario classes and determine probabilities.

**Table 2. Example Latin Square for event classes based on two generalized event classes (Θ and Ψ)**

| Event Class | Ψ (P = 0.05) | $\Psi^-$ (P = 0.95) | Sum |
|---|---|---|---|
| **Θ (P = 0.9)** | **ΘΨ** (P = 0.045) | $\mathbf{\Theta^-\Psi}$ (P = 0.855) | 0.9 |
| $\mathbf{\Theta^-}$ **(P = 0.1)** | $\mathbf{\Theta\Psi^-}$ (P = .005) | $\mathbf{\Theta^-\Psi^-}$ (P = 0.095) | 0.1 |
| SUM | 0.05 | 0.95 | 1 |

## 4.3 TOTAL SYSTEM PERFORMANCE ASSESSMENT METHODOLOGY: MODEL ABSTRACTION

In its review of DOE's TSPAs leading up to and including a prospective LA, the staff will evaluate key elements of the repository system as to the effectiveness of the overall system to protect public health and safety. The staff is developing a systematic approach to reviewing DOE's TSPAs. As currently envisioned by the staff, the approach is hierarchical, as illustrated in Figure 3. The focal point is the overall repository system, where the performance measure is likely to be the expected annual dose to the average member of the critical group during the performance period of interest. To facilitate review of DOE's TSPAs and to focus NRC's review on the most important subsystems, staff will examine the contribution to performance and capability of each of three repository subsystems: engineered system, geosphere, and biosphere, as shown in the middle tier of Figure 3. Each of these subsystems is further subdivided into discrete components of the respective subsystems: engineered barriers that make up the engineered system; UZ flow and transport, saturated zone flow and transport, and direct release to the biosphere; and the dose calculation for the biosphere. Recognizing there are many different ways of dividing the overall system into smaller and analyzable components, this particular division is primarily based on the natural progress of RN release and transport to a receptor group at the YM site. At the base of the hierarchy are the ISIs of the repository system that need to be appropriately abstracted into a TSPA. These ISIs, in general, are the integrated FEPs that could impact system performance. The relationship between these ISIs and the NRC Key Technical Issues is illustrated in Table 3. The judgment about which elements need to be abstracted is based on staff TSPAs performed in the past, review of DOE's TSPAs, and knowledge of the design options for the YM site and YM site characteristics. Because TSPAs are considered iterative, some adjustment of the key elements may occur as future TSPAs and other relevant analyses are completed and site data are collected. In its review, the staff will consider elements of DOE's total system performance demonstration and the relative contributions of repository subsystems or their components to identify those areas that require greater emphasis. The staff will also review DOE's TSPA for completeness and adequacy. Completeness refers to the inclusion of important FEPs that could significantly impact meeting the performance measure. Section 4.2 provides further guidance for completeness. Adequacy refers to how the important features and processes are abstracted and integrated in the TSPA.

It is expected that DOE's TSPA will identify various attributes of the engineered and natural systems and demonstrate their capability to isolate waste. Therefore, the approach delineated in this section will enable the staff to examine systematically, in the context of the total system performance, whether the engineered designs, site characteristics, and interactions among them have been appropriately identified, incorporated, and analyzed in DOE's TSPA. It should be noted that the staff will focus its review to (i) understand the importance to performance of the various assumptions, models, and input data in DOE's TSPA and (ii) ensure that the degree of technical support for models and data abstractions is commensurate with contribution to risk.

For each ISI, those DOE repository safety strategy hypotheses considered pertinent to that ISI can be found in Appendix A. Descriptions of the KTI subissues are listed in Appendix B. The relationship of individual KTI subissues to a particular ISI is also described in Chapter 3 of the KTI IRSRs (U.S. Nuclear Regulatory Commission, 1999c–j). Because the staff expects to use the TPA code to review DOE's TSPAs, a summary of the overall conceptual approach in the most recent version of the TPA code is provided in Appendix F as supporting documentation.

Staff review of DOE's TSPAs will be performed on individual ISIs to determine the acceptability of DOE's model abstraction(s). The staff recognizes that models used in DOE's TSPAs may range from highly complex process-level models to simplified models such as response surfaces or look-up tables. The question of adequacy applies equally to any model, without concern for the level of complexity. This review of model abstractions will be performed by multi-disciplinary ISI teams and will be based on five generic technical acceptance criteria (T1 to T5 in YMRP). The programmatic acceptance criteria in the YMRP apply to all ISIs.

### 4.3.1 Engineered System

The engineered system is composed of an Engineered Barriers component (Figure 3). The Engineered Barriers component represents the engineered barriers and the interaction of the engineered barriers with the expected local environments. It is further partitioned into four integrated subissues: waste package, drip shield, waste form, and the surrounding engineered environment. To evaluate the contribution the engineered system makes to meeting the overall performance objective, each integrated subissue will need to satisfy detailed technical acceptance criteria.

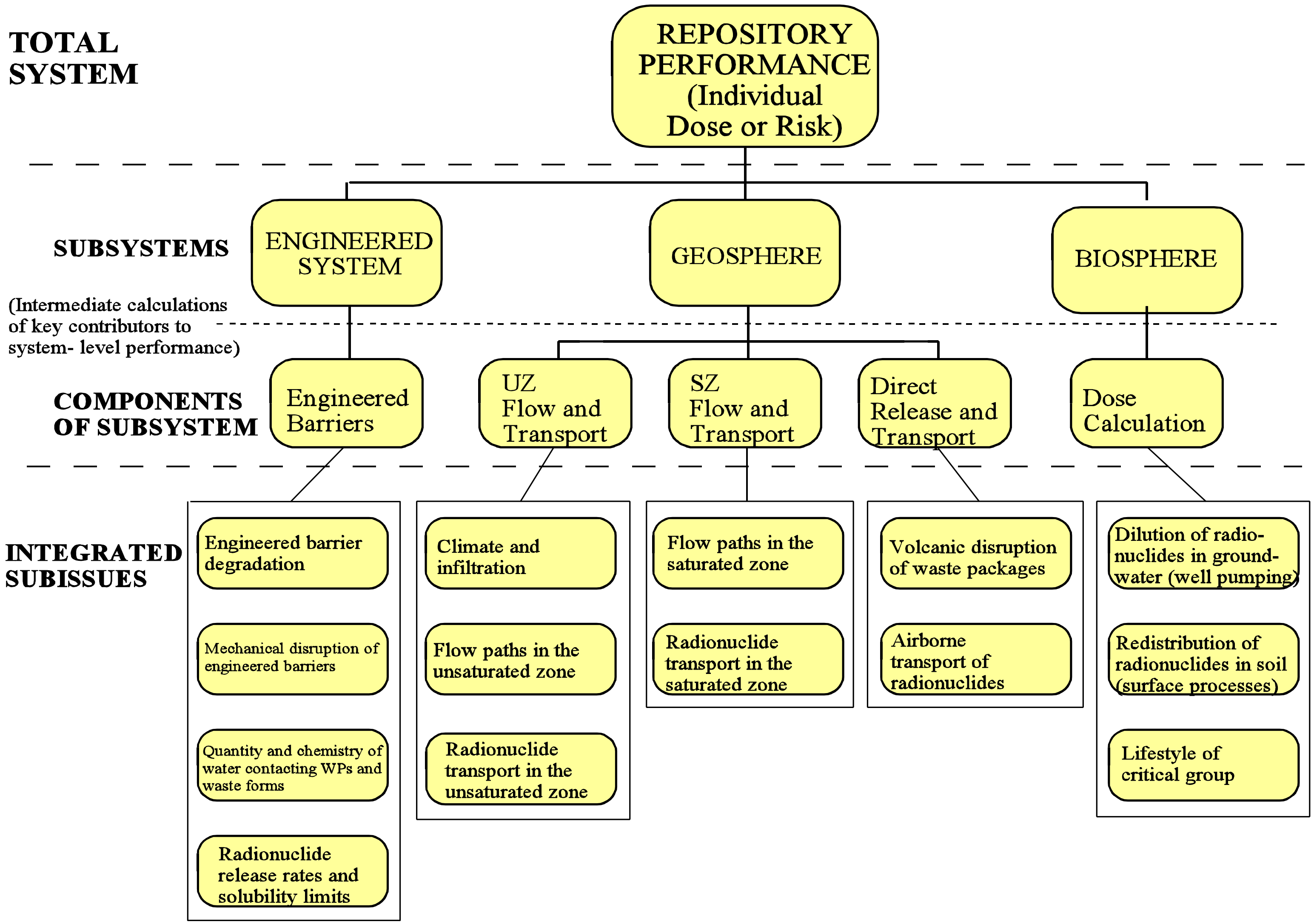



**Figure 3. Flowdown diagram for Total System Performance Assessment**

## Table 3. Relationships between Integrated Subissues and Key Technical Issues

| KTI Subissue* | Integrated Subissues | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **ENG1** | **ENG2** | **ENG3** | **ENG4** | **UZ1** | **UZ2** | **UZ3** | **SZ1** | **SZ2** | **Direct1** | **Direct2** | **Dose1** | **Dose2** | **Dose3** |
| USFIC1 | | | | | ■ | | | | | | | | | ■ |
| USFIC2 | | | | | ■ | | | ■ | | | | | | ■ |
| USFIC3 | | | | | ■ | | | | | | | | | ■ |
| USFIC4 | | | ■ | | | ■ | ■ | | | | | | | |
| USFIC5 | | | | | | | | ■ | ■ | | | ■ | | ■ |
| USFIC6 | | | | | | | ■ | | ■ | | | | | |
| TEF1 | ■ | | ■ | | | ■ | | | | | | | | |
| TEF2 | ■ | | ■ | | | ■ | | | | | | | | |
| TEF3 | | | | | | | | | | | | | | |
| ENFE1 | | | ■ | | | ■ | | | | | | | | |
| ENFE2 | ■ | | ■ | | | | | | | | | | | |
| ENFE3 | | | ■ | ■ | | | | | | | | | | |
| ENFE4 | | | | ■ | | | ■ | | | | | | | |
| ENFE5 | | | | ■ | | | | | | | | | | |
| CLST1 | ■ | ■ | ■ | | | | | | | ■ | | | | |
| CLST2 | ■ | ■ | | | | | | | | ■ | | | | |
| CLST3 | | | ■ | ■ | | | | | | | | | | |
| CLST4 | | | ■ | ■ | | | | | | | | | | |
| CLST5 | ■ | ■ | | ■ | | | | | | | | | | |
| CLST6 | ■ | ■ | ■ | ■ | | | | | | | | | | |
| RT1 | | | | | | | ■ | | ■ | | | | | |
| RT2 | | | | | | | | | ■ | | | | | |
| RT3 | | | | | | | ■ | | ■ | | | | | ■ |
| RT4 | | | | | | | ■ | | ■ | | | | | |
| TSPAI1 † | | | | | | | | | | | | | | |
| TSPAI2 † | | | | | | | | | | | | | | |
| TSPAI3 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| TSPAI4 † | | | | | | | | | | | | | | |
| IA1 † | | | | | | | | | | | | | | |
| IA2 | | ■ | | | | | | | | ■ | ■ | | ■ | ■ |
| SDS1 ‡ | | ■ | | | | | | ■ | | | | | | |
| SDS2 | | ■ | | | | | | | | | | | | |
| SDS3 | | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | | | | | |
| SDS4 ‡ | | ■ | | | | | | | | | | | | |
| RDTME1 † | | | | | | | | | | | | | | |
| RDTME2 | | ■ | | | | ■ | | | | | | | | |
| RDTME3 | ■ | ■ | ■ | | | ■ | | | | | | | | |
| RDTME4 † | ■ | | | | | | | | | | | | | |

| | | | |
|---|---|---|---|
| ENG1 | ENG–Degradation of Engineered Barriers | SZ1 | GEO–Flow Paths in the Saturated Zone |
| ENG2 | ENG–Mechanical Disruption of Engineered Barriers | SZ2 | GEO–Radionuclide Transport in the Saturated Zone |
| ENG3 | ENG–Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms | Direct1 | GEO–Volcanic Disruption of Waste Packages |
| | | Direct2 | GEO–Airborne Transport of Radionuclides |
| ENG4 | ENG–Radionuclide Release Rates and Solubility Limits | Dose1 | BIO–Dilution of Radionuclides in Groundwater due to Well Pumping |
| UZ1 | GEO–Climate and Infiltration | | |
| UZ2 | GEO–Flow Paths in the Unsaturated Zone | Dose2 | BIO–Redistribution of Radionuclides in Soil |
| UZ3 | GEO–Radionuclide Transport in the Unsaturated Zone | Dose3 | BIO–Lifestyle of the Critical Group |

*Appendix B provides a description of the KTI subissues.
†These subissues are addressed in areas other than model abstraction.
‡The influence of SDS4 (Tectonic model) and SDS1 (Faulting) on Direct1 (Volcanic Disruption of Waste Packages) will be discussed in scenario analysis in future revisions of this report. This is a result of SDS1 and SDS4 potentially affecting the probability of igneous activity.

#### 4.3.1.1 Engineered Barriers

In this section, technical basis for review of the four ISIs in the engineered barriers abstraction, as identified in Figure 3 (i.e., Engineered Barrier Degradation, Mechanical Disruption of the Engineered Barriers, Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms, and Radionuclide Release Rates and Solubility Limits) are discussed. The key elements for this abstraction were derived from staff experience with previous and current performance assessment activities, review of DOE's TSPAs, sensitivity studies performed at the process and system levels, and review of DOE's hypotheses in its Repository Safety Strategy (U.S. Department of Energy, 1998b). As previously noted, these ISIs represent the essential factors to be considered in demonstrating the engineered barriers' capability to improve total system performance. To evaluate the contribution the engineered system makes to meeting the system performance objective, the current approach is to focus on intermediate calculations providing the distribution of RN release rates, as a function of time, from the engineered system.

##### 4.3.1.1.1 Engineered Barrier Degradation

The discussions and technical basis on the engineered barrier degradation abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The engineered barrier degradation ISI addresses the assessment of engineered barrier performance including waste package lifetimes. This ISI is derived from the engineered barriers component of the engineered system subsystem (Figure 3). Figure 4 is a diagram illustrating the relationships between engineered barrier degradation and other ISIs.

The engineered barrier degradation ISI considers the individual and combined effects of FEPs relevant to the containment of radionuclides within the engineered barrier system. Engineered barriers in the repository system include drip shields, waste packages, and backfill. Degradation modes of the engineered barriers may include corrosion processes such as uniform corrosion, pitting corrosion, crevice corrosion, intergranular corrosion, stress corrosion cracking (SCC), microbially-influenced corrosion, and hydrogen embrittlement (HE). The effects of fabrication and welding processes and design options, such as backfill and WP coatings, on the possible engineered barrier degradation modes also must be evaluated.

Corrosion is considered the primary degradation process of the engineered barriers. The evolution of the near-field environment and coupled THC processes will affect the chemistry, temperature, and pH of the environment contacting the engineered barriers and also will have a strong influence on both the type and rate of the degradation processes. Condensation and flow of chloride-containing groundwater to the engineered barriers may begin localized corrosion processes. TM processes such as rockfall and seismic activity may lead to application of additional stresses to the engineered barriers and promote SCC. In addition, rockfall and seismic activity may result in the failure of the engineered barriers that have been degraded by the various corrosion processes. Igneous activity may affect the integrity of the engineered barriers as a result of thermal, mechanical, and chemical interactions.

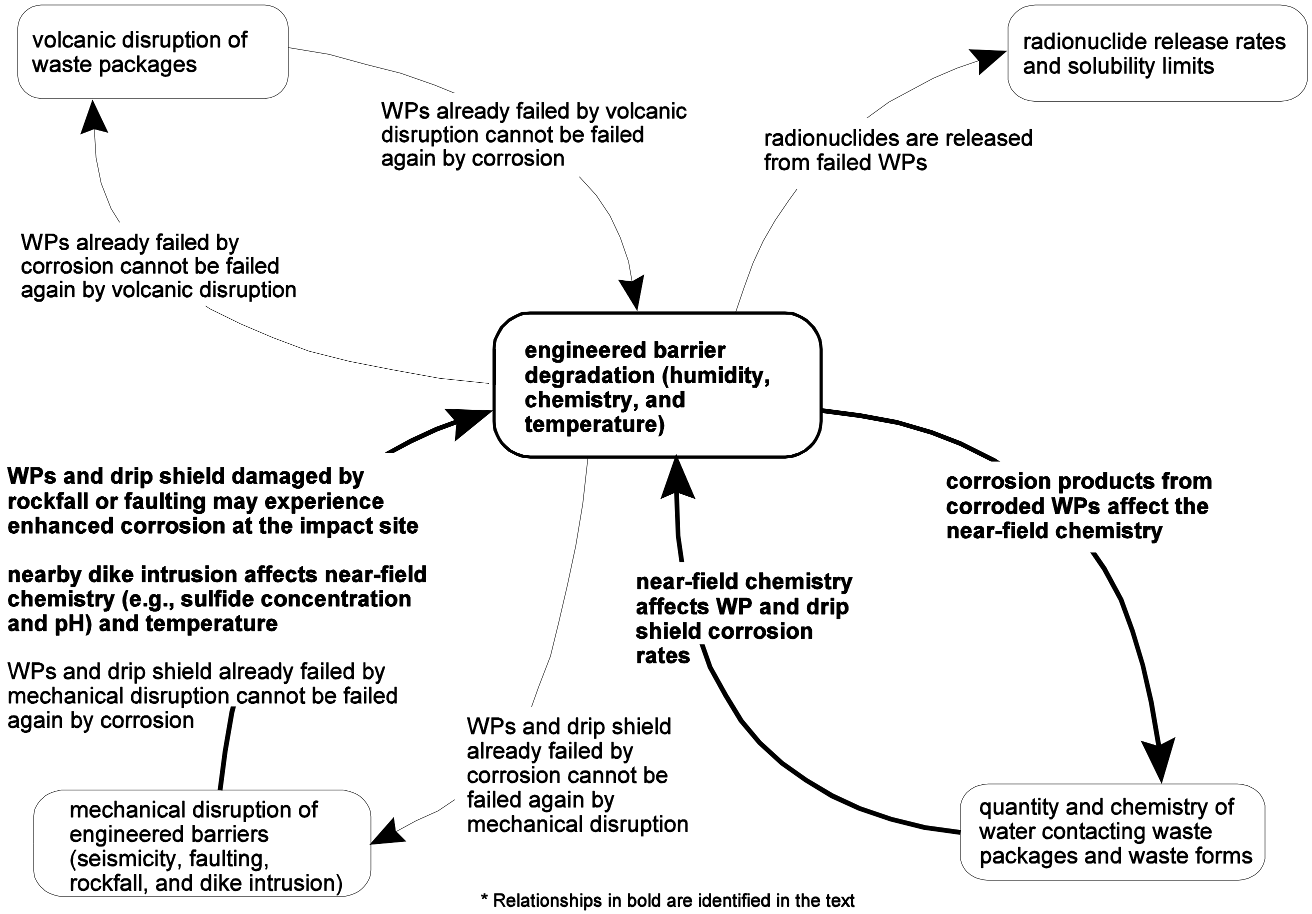



**Figure 4. Diagram of the relationships between "engineered barrier degradation" and other integrated subissues**

The waste package is the primary engineered barrier in the geologic repository planned at Yucca Mountain, Nevada.  The ability of the WP to contain and, in the long term, limit release of radionuclides is primarily determined by the long-term corrosion resistance of waste package materials.  The waste package is, therefore, key to providing reasonable assurance that the total system performance objective can be met by isolating wastes during the initial stages of disposal when radionuclides with short half-lives are abundant and by limiting release of radionuclides with long half-lives during extended periods of time.  Additional components of the EBS, such as dripshields and backfill, are planned to enhance the performance of the WP.

The WP degradation has been shown to be important to waste isolation at the proposed YM repository (Wescott, et al., 1995; U.S. Department of Energy, 1998a; Kessler and McGuire, 1996). NRC sensitivity analyses have shown that the simulated performance of the proposed YM repository (for the 10,000 year time period of interest) was strongly influenced by the WP lifetime (Mohanty, et al., 1999).  The contribution to performance of other components of the EBS has not been extensively investigated.  In this version of the IRSR, the focus is on the WPs until the performance of EBS (drip shields, and other barriers) is better understood.

The following are examples of possible important physical phenomena and couplings with other ISIs (illustrated in Figure 4):

- Seismic (and possibly fault formation) mechanical disruptions may create weak spots on the WP for enhanced corrosion.  Nearby dike intrusions into the repository will change, for example, both the near-field temperature and chemistry to which the WP is exposed for some length of time (mechanical disruption of WPs).

- Near-field chemistry (e.g., pH, chloride concentration, dissolved oxygen concentration, and carbonate/bicarbonate concentration) affects the WP corrosion rate and can affect the corrosion mode.  Corrosion products from corroded WPs affect the near-field chemistry (quantity and chemistry of water contacting WPs and waste forms).

Container lifetimes and dose to the receptor group have been independently calculated using the NRC TPA Version 3.2 code for the repository and WP design presented in the VA.  Both uniform corrosion and localized corrosion are considered in the TPA code.  Dry oxidation of the carbon steel overpack is not considered to be a significant container degradation mode and should result in only a shallow penetration of the container (Ahn, 1996; Larore and Rapp, 1996; Henshall, 1996; U.S. Nuclear Regulatory Commission, 1999e).

The occurrence of wet (humid air and aqueous) corrosion is determined by the relative humidity (RH) at the WP surface.  Typically, a threshold value for RH, called the critical RH, which depends on temperature and the presence of a salt layer on the surface of the overpack, is considered in calculating the time at which wet corrosion initiates (Mohanty, et al., 1997).  The critical RH can be a relatively uncertain value because its determination depends on the sensitivity of the corrosion rate-measuring instrumentation.

Under aqueous corrosion conditions, the corrosion mode of the carbon steel overpack material is dependent on the temperature and the chemistry of the near-field environment (Sridhar, et al., 1994).  At neutral and acidic pH values, the corrosion is essentially uniform in nature. At pH values of approximately 9 or higher, where passivation occurs, carbon steel undergoes localized corrosion in the presence of deleterious species such as chlorides.  Numerous pits can be nucleated across the container surface, the maximum depth of pitting and eventual penetration of the outer overpack wall can be calculated using extreme value statistical principles (Marsh, et al., 1985). It has also been shown that acidic conditions can prevail in pits due to the hydrolysis of the ferrous ions (Sridhar and Dunn, 1994).

Uniform corrosion rates, for the corrosion resistant Alloy 22 containers, are based on the passive current density of the alloy measured in chloride containing solutions, whereas the susceptibility of the alloy to localized corrosion is determined by the corrosion potential ($E_{corr}$) and the repassivation potential ($E_{rp}$) (U.S. Nuclear Regulatory Commission, 1999e). The corrosion potential is dependent on the partial pressure of oxygen, temperature, pH, the presence of other redox species, and the passive current density. The repassivation potential is dependent on the logarithm of the chloride concentration and temperature. Recent work also shows that the repassivation potential of the alloy can be reduced, and thus the alloy becomes more susceptible to localized corrosion, by welding and thermal aging (Dunn, et al., 1999). Uniform corrosion of Alloy 22 is expected under aqueous conditions when the corrosion potential is less than the repassivation potential. On the other hand, when the repassivation potential exceeds the corrosion potential, localized corrosion is assumed to initiate without an induction time. The localized corrosion penetration rate is assumed to be constant at 0.25 mm per year.

Sensitivity analyses performed with the TPA code indicate that two parameters related to the conditions in the near-field environment, the partial pressure of oxygen and the chloride concentration, may have a significant effect on container failure and lead to enhanced radionuclide release (U.S. Nuclear Regulatory Commission, 1999e). Increases in the partial pressure of oxygen and chloride concentration promoted localized corrosion of the carbon steel overpacks. Although pH is not a sampled parameter in the TPA code, it would also be expected to be a factor in the initiation of localized corrosion. $E_{rp}$ measurements conducted with Alloy 22 specimens indicate that localized corrosion may be initiated in concentrated chloride solutions (Dunn, et al., 1999). The susceptibility to localized corrosion increased when Alloy 22 was either welded or thermally aged.

The passive corrosion rate of Alloy 22 had a significant effect on both the failure time and dose to the receptor group (U.S. Nuclear Regulatory Commission, 1999e). Using the basecase corrosion rate of $5.9 \times 10^{-4}$ to $1.9 \times 10^{-3}$ mm per year, the first WP failure (VA design) occurred in approximately 10,000 years and all waste packages failed in 46,000 years. Using experimentally determined passive corrosion rates, the first waste package failure occurrs after 30,000 years, and 80 percent of the WPs fail after 100,000 years (U.S. Nuclear Regulatory Commission, 1999e).

Segregation of alloying elements during weld solidification and the formation of secondary phases that are detrimental to both the mechanical properties and the corrosion resistance of the materials have been observed in Alloy 22 welds (Cieslak, et al., 1986). The formation of topologically close packed (TCP) phases such as μ- and P- phase typically form within the grain boundary region and contain high concentration of Mo and W. Because Mo and W are known to provide resistance to localized corrosion, incorporation of these alloying elements into the TCP phases can be expected to render the alloy more susceptible to localized corrosion at the grain boundaries.

#### 4.3.1.1.2 Mechanical Disruption of Engineered Barriers

The discussions and technical basis on the mechanical disruption of engineered barriers abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The mechanical disruption of engineered barriers ISI addresses possible engineered barriers component failures arising from faulting-induced shear, seismicity-induced drift collapse and WP shaking, and igneous intrusion. The mechanical disruption of engineered barriers ISI is derived from the engineered barriers component of the engineered subsystem (Figure 3). The relationships between engineered barrier degradation and other ISIs are illustrated in Figure 5.

Mechanical disruption of engineered barriers evaluates potential failure modes of the waste packages, drip shields, backfill, and related components of the engineered subsystem associated with the emplacement drifts that could result from faulting, earthquakes, and igneous intrusion during the proposed 10,000-year lifetime of the repository. For faulting, the principal concern is whether a direct fault displacement in the repository could shear vital engineered components, especially WPs. For seismicity, the principal concern is whether local and regional earthquakes could generate enough ground shaking in the repository to cause roof or pillar collapse of the emplacement drifts. The resulting rockfall blocks may be sufficient in size to damage vital engineered components, including WPs. In addition, seismicity may cause alteration of WP internal configuration from a subcritical formation to a critical or super critical formation directly or indirectly, through falling rocks. The super critical formation could result in ruptures of cladding and further damage to WPs. For igneous intrusions, the principal concern is whether dense, basaltic magma at high temperatures could impact and damage or fail components of engineered barriers. In addition, the adverse thermal, chemical, and mechanical effects of an igneous intrusion may compromise the WP confinement function. Including the effects of these disruptive events into the abstraction of this ISI and, subsequently, into the total system performance assessment calculations requires: (i) the recurrence rate, magnitude, and style of faulting in the repository; (ii) fault characteristics, such as fault length, width, dip, orientation, and displacement; (iii) the recurrence rate, magnitude, and ground motion of earthquakes at the repository; (iv) rockfall characteristics, such as yield-zone height and fracture density, orientation, and spacing; (v) rockmass properties such as strength, rigidity, and density; (vi) the recurrence rate, extent of the affected area, and style of igneous intrusion within the repository emplacement drifts; (vii) intrusive magma flow characteristics, such as temperature, chemical composition, and flow rate; and (viii) engineered barrier characteristics, such as structural strength and rigidity of WPs, backfill, liners, and drip shields.

Damage to the various engineered barriers components and possible release of radionuclides from the WPs depends on initial integrity and evolution of the various possible corrosive processes over time. For these calculations, the Mechanical Disruption of Engineered Barriers ISI relies on material properties of the engineered barriers components and associated corrosion models supplied by the CLST KTI. Parameters that define the recurrence rate, magnitude, style, and characteristics of faulting and seismicity are supplied by the SDS KTI, as are parameters and models that define fracture density, orientation, and spacing. The fracture and seismicity data are used by the RDTME KTI, in conjunction with thermomechanical models, to simulate roof and pillar collapse. Moreover, the state of rock stress around the repository drifts will affect how ascending magma interacts with the drifts and, in turn the engineered barriers. Rock stress is controlled by the distribution of regional tectonic stress and likely TM effects associated with HLW emplacement. If magma enters the repository drift, the number of WPs impacted will depend on the repository design, the presence of backfill, drip shields, and WP spacing. Performance assessment calculations for the mechanical disruption of engineered barriers require all these inputs, and thus all are considered to contribute equally to the ISI. The outputs from this ISI affect radionuclide release rates, governed by models of the WP failure modes (pinhole, breach, or complete dismemberment), the amount of water contacting the WPs, and subsequently, the groundwater

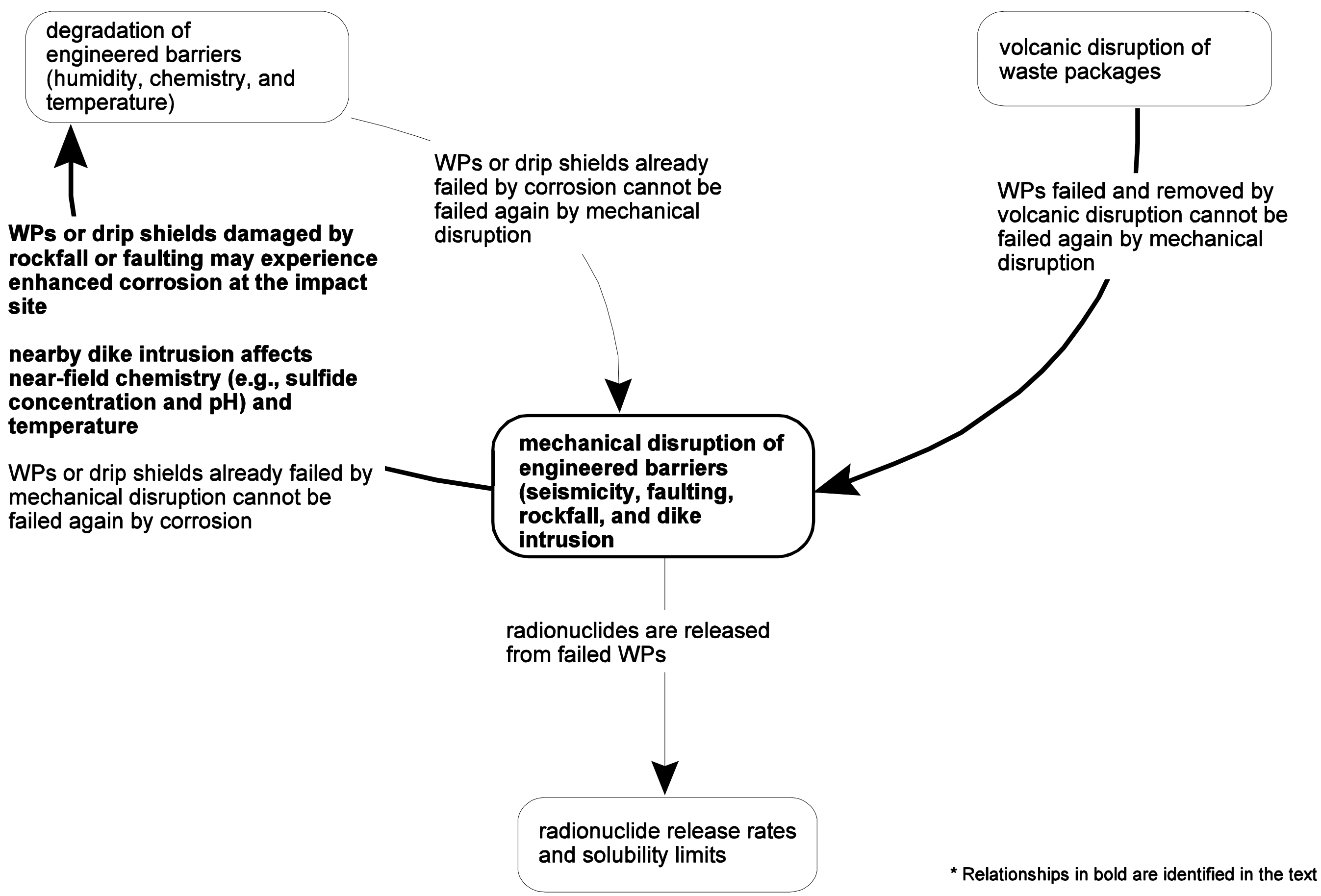



**Figure 5. Diagram of the relationships between "mechanical disruption of engineered barriers" and other integrated subissues**

travel times. These are all important because of the lag time they provide between initial WP failure and subsequent release to the critical group.

Under the design proposed by the DOE in the VA report (U.S. Department of Energy, 1998a) and based on current geological, geophysical, and geotechnical data on faulting, seismicity, and rockfall, mechanical disruption of the engineered barriers does not appear to be important to system performance (U.S. Department of Energy, 1998a; U.S. Nuclear Regulatory Commission, 1999f,g and references therein). WP failures and associated premature releases of RNs to the accessible environment are too infrequent, too small, and occur too late within the proposed 10,000-year compliance period to adversely affect dose or risk. Preliminary PA calculations (Mohanty, et al., 1999) indicate probability weighted WP failures from faulting and seismicity of less than two per 10,000-year realization. Delivery of the released RNs is through the groundwater transportation pathway, and current estimates indicate groundwater travel times in excess of several thousand years (U.S. Nuclear Regulatory Commission, 1999h). WP failures from faulting and seismicity occur randomly in time, and given the long groundwater travel time, those that fail late in the 10,000-year performance period are of no consequence.

Intrusive igneous disruption of engineered barriers, however, could involve a larger number of WPs failing in a single event. The volume of Yucca Mountain Region (YMR) igneous events is on the order of $10^6$–$10^8$ $m^3$, whereas the volume of the repository is on the order of $10^6$ $m^3$. Intrusive IA currently represents a process that could cause a large number of WPs to fail simultaneously during the first 10,000 years after postclosure without their contents being released directly to the surface. Subsequent HLW release into the accessible environment is through hydrologic flow and transport. Although a large number of WPs may fail during the igneous event, the annual probability of intrusive igneous disruption is on the order of $5 \times 10^{-7}$ (U.S. Nuclear Regulatory Commission, 1999i). As a consequence, the contribution to peak expected annual dose from intrusive igneous disruption is likely to be small compared to the peak expected annual dose from undisturbed repository operations during the first 10,000 years following closure. Detailed discussions of the underlying technical bases are presented in the IA IRSR (U.S. Nuclear Regulatory Commission, 1999i). The affects of extrusive igneous events on repository performance are discussed in Section 4.3.2.3.1 of this IRSR.

Performance assessment of other mechanical failure mechanisms of the WPs or other components of the EBSs other than fault rupture, seismically-induced rockfall, and igneous intrusion such as damage to the WP caused by motion of the WP initiated by a seismic event have not been investigated yet. Mechanical disruption effects could also affect the degradation rates of engineered barriers by providing sources of suddenly applied stress that may enhance corrosion processes such as SCC. It needs to be emphasized, however, that the corrosion models presently employed within the TSPA code do not account for these effects (U.S. Nuclear Regulatory Commission, 1999e). In addition, the DOE recently proposed significant design changes to the engineered barriers that include partial or complete backfill of the drifts, changes in the composition and layout of the drift liners, and the addition of drip shields (U.S. Department of Energy, 1999b). Performance assessment calculations associated with these design changes have not been presented in a TSPA and, as a result, the importance of the mechanical disruption of these components of the engineered barriers to repository performance needs to be examined.

The following is an example of possible important physical phenomena and coupling with another ISI (see Figure 5):

- Seismic (and possibly other) mechanical disruptions may damage the WP surface and thereby enhance corrosion. Nearby dike intrusions in the vicinity of the repository affect the near-field chemistry (WP corrosion).

Yucca Mountain is located within the central Basin and Range Province of the North American Cordillera, a region characterized by complex interactions of strike slip and extensional deformation, active since the onset of the Cenozoic Era some 65 million years ago. The region remains tectonically active, as indicated by numerous Quaternary faults and volcanism (last 2 Ma), including evidence for Holocene (last 10,000 years) faulting. There is also a rich historic seismic record, including the 1992 Little Skull Mountain earthquake, which had a magnitude of 5.6. Given the active tectonic setting of YM, future seismotectonic activities could affect the stability of the engineered barriers and pose a potential risk of noncompliance with radiological safety, health, and environmental protection standards.

Detailed technical bases for abstractions of mechanical disruption for engineered barriers are presented in the CLST, SDS, and RDTME IRSRs (U.S. Nuclear Regulatory Commission, 1999e,f,g). A summary is provided here to highlight those aspects of the technical bases critical to PA abstractions and associated input parameters.

Earthquake Hazard

A critical input parameter to performance assessment abstractions of mechanical disruptions of engineered systems are the probabilities of different levels of earthquake-induced vibratory ground motions. The Probabilistic Seismic Hazard Analysis (PSHA) methodology has been identified by the NRC in 10 CFR 100.23 as an appropriate approach to address uncertainties associated with ground motion. The DOE has outlined the methodology used for a PSHA in Topical Report #1 (U.S. Department of Energy, 1997a). This approach has been accepted in principle by the NRC (Bell, 1996). The methodologies recommended in the Senior Seismic Hazard Analysis Committee Report (U.S. Nuclear Regulatory Commission, 1997b) also offer acceptable approaches for evaluating the probabilistic seismic hazard at YM. The PSHA methodology allows uncertainties inherent in predicting future ground motions (and fault displacements) to be explicitly incorporated into the hazard assessment. The PSHA methodology consists of three parts: (i) seismic source characterization, including fault and aeral sources and their associated recurrence relationships; (ii) ground-motion attenuation characterization, including any special effects for different earthquake sources and wave-path propagation; and (iii) probabilistic calculation, including incorporation of both aleatoric and epistemic uncertainties.

Seismically Induced Rockfall

Seismicity is a disruptive event that needs adequate consideration in both repository design and performance assessment. Seismicity could affect repository performance by producing rockfall that may damage WPs and shaking that may cause criticality within the WPs. The potential effects on the performance of WPs are twofold. The first possible effect of rockfall is to rupture WPs by the impact produced by the falling rock. The second aspect is that rockfall may cause damage to the container outer pack in a manner that corrosion of the WPs will accelerate and thus reduce the intended service life of WPs. To perform an adequate assessment of the effect of rockfall due to either thermomechanical load or seismicity, a number of factors will need to be understood better, such as the design of WPs, repository design (ground supports and backfills), and potential size of rockfall. Equally important is the availability of a reasonable model/approach that can be used to perform such an assessment.

The analyses of rockfall should explicitly account for four basic aspects: (i) size distribution of individual blocks that can potentially fall; (ii) possibility of multiple blocks falling onto a WP simultaneously; (iii) vertical and lateral extent of the region undergoing rockfall; and (iv) effects of repeated rockfall on the (corroded) canister due to repeated seismic events. These aspects of rockfall analyses are discussed in this section, with emphasis on specific needs for analyses, appropriateness of methodologies, and sufficiency of input considerations and associated uncertainties. The discussion is based mainly on data from YM site characterization activities, current DOE approaches, and ongoing modeling efforts at NRC/Center for Nuclear Waste Regulatory Analyses (CNWRA). The ultimate goal of these analyses is to give technically adequate estimation of the volume range and quantity of rock blocks that have the potential to fall onto the WPs so as to evaluate the effects of such rockfall on the integrity of the WPs. Because characterizing rockfall is a recently initiated ongoing effort, the technical bases provided in this section of the IRSR are not completely developed and, therefore, should be considered preliminary.

At YM, an earlier attempt to estimate size distribution of rock blocks was made by Gauthier, et al. (1995) using a modified (log-space) version of the Topopah Spring fracture spacing distribution developed by Schenker, et al. (1995). It is a two-dimensional (2D) analysis based on the North Ramp Geotechnical core hole, the Exploratory Studies Facility (ESF) data, and the assumption of cubic and parallelepiped blocks. Assumptions of cubic or parallelepiped block shape may distort the estimation of size distribution of *in situ* blocks due to various assumptions about the extent of fractures in the third dimension. Recently, DOE conducted Key Block analyses in three dimensions using DRKBA (Stone Mineral Ventures, Inc., 1998). In this software, fracture sets are identified based on clustering of fracture poles projected on stereonets, and probabilistic distributions of fracture parameters (Fisher constant, orientation, spacing, and trace length) are determined for each set. Fracture planes are then simulated by a Monte Carlo technique from probability distributions of fracture parameters. Finally, volume distributions of the key blocks per unit drift length are determined for various lithologic units (Tptpul, Tptpmn, Tptpll, and Tptpln) and for different drift orientations.

In the staff's opinion, the Key Block analyses can be used to estimate rockfalls that are random in nature and occur under gravity, as well as a likely failure-initiation location of a rockfall event. Rockfalls caused by thermal load and/or earthquake ground-motion events need to be determined through thermal and dynamic analyses. In the case of earthquake-induced rockfall, rockfall frequency depends on the frequency of ground-motion events. In thermal-load induced rockfall, frequency may be a time function of the evolution of the thermal load and the degradation of rock properties.

Thermomechanical analyses at the drift scale up to 100 years (Ahola, et al., 1996; Chen, et al., 1998) show that thermal loading causes significant stress redistribution around the drift. The study considered a single drift in a rock mass that had a regular joint pattern with two joint sets (subhorizontal and subvertical). The analyses were conducted using the computer code UDEC (Itasca Consulting Group, Inc., 1996). The thermal load increased the maximum compressive stress, and rotated its direction from vertical to horizontal. The location of the highest compressive stress region shifted from the side walls to roof and floor areas of the drift. Failure along side walls due to concentration of compressive stresses and lack of lateral support in underground mines and tunnels is a frequently observed phenomenon. When such compressive stress is rotated and shifted to the roof area, a similar phenomenon could occur and thus cause rockfall.

This study also reveals that thermal load could increase failure of intact rock blocks. Other studies have observed this phenomenon (Tsai, 1996; CRWMS M&O, 1995a). Although failure zones in most cases were localized to the immediate areas around the drift, in some cases they extended to the middle of the pillar in rock masses that are weaker and have a higher thermal expansion coefficient. Although failure of intact rock in discontinuum analysis may not be the direct evidence of explicit rockfall, it represents a failure or damage state and indicates the need to establish a criterion for determining the vertical extent of potential rockfall with appropriate modeling methodologies and input parameters (e.g., joint patterns representative of the site).

Rockfall phenomena were analyzed by simulating the behavior of an unsupported emplacement drift undergoing repeated seismic ground motion after subjecting it to *in situ* stress and, in some cases, a time-decaying thermal load generated by the emplaced wastes (Chen, 1998, 1999). The analyses used the distinct element computer code UDEC (Itasca Consulting Group, Inc., 1996). Modeling results show that, in most cases, multiple rock blocks (rather than a single rock block) fall simultaneously during seismic ground motion. Fracture patterns have controlling effects on the amount of simulated rockfall. In these analyses, a regular fracture pattern refers to a fracture network with two or more sets of fractures of infinite length and constant orientation and spacing. An irregular fracture pattern refers to a fracture network defined by certain statistical distributions of fracture parameters such as orientation, spacing, trace length, and gap length. Fracture patterns become more complex as the number of fracture sets and variations of parameters increase and spacing decreases. Modeling results show that with increasing complexity of fracture patterns, the number of rock blocks falling, the extent of the rockfall region, and the overall drift instability increase. In general, the amount of simulated rockfall for a heated drift is less than that of an unheated drift with the same fracture pattern because the thermal compressive stress tends to reduce fracture normal displacement. A similar phenomenon was observed by Fairhurst (1999). A second ground-motion event usually produces little additional rockfall.

Dynamic modeling results also show that the stress distribution is altered significantly by thermal load and, to a lesser degree, by dynamic load. As mentioned previously, the superposition of thermal stresses on excavation-induced mechanical stresses changes the location of the maximum principal stress from drift sidewalls (nearly vertical) to roof and floor (nearly horizontal). In most cases, a zone of tensile minimum principal stress occurs in the roof and floor. Modeling has demonstrated, that the extent of the region with tensile minimum principal stress (positive stress) is greater for an irregular fracture pattern than that for a regular fracture pattern, causing more extensive rockfall in the case of an irregular fracture pattern.

It is desirable to establish a criterion that could be used to determine the maximum vertical extent of potential rockfall. The extent of rockfall will depend on factors such as level of ground motion, joint pattern, individual block sizes, thermal and mechanical properties of the rock mass, joint shear and normal displacements, joint shear and normal stresses, and joint strength.

Dynamic modeling results show that of all these factors, fracture pattern may have the most significant effect on rockfall. Therefore, analyses using a regular fracture pattern may not be conservative. An ongoing effort at CNWRA is to simulate fracture network patterns representative of the *in situ* conditions based on mapping and scanline data from the ESF and Cross Drift. Future dynamic analyses will incorporate more realistic fracture patterns and recent changes in DOE repository design.

Faulting

Fault displacement analyses evaluates the potential hazards of an intersection of an active fault with vital components of the repository system, especially WPs. For this evaluation of faulting, both principal (including sympathetic) and secondary (or distributed) faulting must be considered (as defined in dePolo, et al., 1991). Principal faulting refers to displacement along the main fault zone responsible for the release of seismic energy (i.e., an earthquake). At YM, principal faulting is assumed to occur only on primary faults, mainly block-bounding faults. In contrast, secondary or distributed faulting is defined as rupture of smaller faults that occurs in response to the rupture in the vicinity of the principal fault. These two subsets of faults are not mutually exclusive. Faults capable of principal rupture themselves can undergo secondary faulting in response to faulting on another primary fault. Because principal and secondary faults pose a potential risk to repository performance, both types must be considered.

The simplest approach for the evaluations of principal faulting, and one that was used predominantly before 1998 for siting of nuclear reactors and other critical facilities, is a deterministic analysis. In that approach, capable faults (10 CFR Part 100, Appendix A) are avoided by adequate setback distances. This approach may not be appropriate for YM (Coppersmith, 1996) because of the different performance requirements between a reactor and the repository. The proposed repository is too extensive to reasonably expect that virtually all faults of concern will fall outside its boundaries.

Methods similar to the PSHA have also been developed to evaluate fault displacement hazards, especially for principal faults for which detailed paleoseismic data are available. These methods construct individual fault displacement hazard curves, analogous to probabilistic seismic hazard curves, for each principal fault (Youngs and Coppersmith, 1985; U.S. Geological Survey, 1998).

Igneous Intrusion

Many of the parameters necessary for calculating the dose consequences of volcanic disruptions of the proposed repository can be bounded only through modeling. Ascending magma that intersects a repository drift encounters variations in lithostatic confining pressure that have not occurred at analog volcanoes. The NRC staff currently is conducting numerical and analog laboratory experimental modeling to evaluate how ascending magma may flow after intersecting a repository drift, because these effects may affect the number of WPs impacted during a repository-penetrating igneous event (U.S. Nuclear Regulatory Commission, 1999i). Ascending magma has an overpressure on the order of 10 MPa greater than lithostatic pressure. If the magma encounters an open or partially backfilled drift, it may expand, accelerate to high velocities (10–100 m per second), and flow into available open spaces.

For a nonbackfilled drift, magma may fill the entire drift on the order of minutes, or less, and be in contact with all WPs in the drift. Because basaltic intrusions at 300 m below the surface commonly are at least 1 km long, multiple drifts may be intersected during a repository-penetrating igneous event. In addition, magma will flow from the point of drift intersection outwards into the drifts until it encounters an opposing pressure equal to the fluid pressure in the magma system. Unless buttressed by consolidated WPs or backfill, magma likely will flow into access drifts and adjacent emplacement drifts until either the volume of the eruption is contained within the drift system or the fluid (i.e., magmatic) pressure exceeds the pressure necessary to open a fracture in the drift walls. Because the volume of the drift system (about $3 \times 10^6$ $m^3$) is smaller than most YMR basaltic eruptions (about $10^6$–$10^8$ $m^3$), only the smallest eruptions could be wholly contained by the drift system. This scenario would assume, however, that all WPs in the drifts have been surrounded by magma and would have been breached.

The extent of magma flow in the presence of backfill has not been evaluated by NRC or DOE. Because the magma system has an overpressure on the order of 10 MPa greater than lithostatic confining pressure at 300-m depths, some compaction of nonconsolidated backfill is likely during igneous disruption. In addition, magma could flow in significant gaps between drift roofs and backfill and in voids between WPs and drip shields.

Other parameters necessary for volcanism risk calculations, primarily related to interactions between basaltic magma and engineered barriers, are also difficult to constrain. The physical, thermal, and chemical loads imparted on a WP impacted by basaltic magma exceed current WP design bases. Although data and models have not evaluated WP behavior under appropriate igneous conditions (e.g., U.S. Department of Energy, 1998a,c), staff conclude that WP failure on contact with basaltic magma is a reasonably conservative assumption (U.S. Nuclear Regulatory Commission, 1999i). Available data and models also have not evaluated HLW behavior under appropriate igneous conditions (e.g., CRWMS M&O, 1998). The physical, thermal, and chemical loads imparted on HLW particles during an igneous intrusive event may induce fragmentation, reducing HLW average particle sizes (U.S. Nuclear Regulatory Commission, 1999i). This will affect subsequent remobilization of RNs in aqueous solutions.

Corrosion Degradation

The NRC considered, in addition to corrosion processes, that engineered barriers may be affected by material instability (i.e., degradation of mechanical properties) owing to prolonged exposure to elevated temperatures (U.S. Nuclear Regulatory Commission, 1999e). Degradation of mechanical properties leading to mechanical failure from residual and/or applied stresses can adversely affect container performance and, ultimately, performance of the repository system. Because the VA design had carbon steel as the outer container, the effect of WP temperature on material stability of carbon steel was evaluated. Staff evaluations (Sridhar, et al., 1994; Cragnolino, et al., 1996) indicated that carbon and low-alloy steels, such as A516 Grade 55 and A387 Grade 22 steels, may experience a substantial decrease in toughness as a consequence of long-term thermal aging at repository temperatures. This phenomenon, which is similar to temper embrittlement, may contribute to premature mechanical failure of outer overpacks. Thermal embrittlement of carbon and low-alloy steels occurs when impurities originally present in the steel, mainly P, segregate to grain boundaries during thermal exposure. The segregation of P may result in reduction of fracture toughness due to a change in the low-temperature fracture mode from transgranular cleavage to intergranular fracture, promoting container failure that can be initiated at flaws under the effect of an impact. Calculations suggest that significant grain boundary P segregation and, hence, the potential for a substantial degradation in toughness of steels, may occur only as a consequence of long-term thermal aging at temperatures greater than 200 °C for several thousand years (Cragnolino, et al., 1998). At lower temperatures, such as those envisioned in TSPA-VA, it appears that thermal embrittlement should not be a matter of concern. Although A516 carbon steel was the material of choice as outer container in VA, it is no longer considered for the site recommendation design.

Thermal stability of corrosion-resistant Ni-base Alloy 22, used as inner container materials in the VA design and outer container material in EDA-II, can also be compromised by prolonged exposures to elevated temperatures. In this case, generation of ordered structures or formation of brittle intermetallic phases may affect mechanical properties or facilitate degradation processes, such as HE. Alloy 22 experiences an ordering transformation when heated in the temperature range of 250–550 °C (Sridhar, et al., 1994; Cragnolino, et al., 1994). The result is an increase in the work hardening rate and, as a consequence, an enhanced susceptibility to SCC and HE. Another possible cause of thermal instability in Alloy 22 arises from the precipitation of brittle intermetallic phases. The existence of long-range ordering of Alloy 22 and the absence of μ phase for aging times of 30,000 and 40,000 hours (3.4 and 4.6 years) at 425 °C has been reported recently (Rebak and Koon, 1998). For Alloy 22, as for carbon steels, these thermal instability effects are more likely to be a concern at high heat loading.

The necessary stresses for mechanical failure to occur as a consequence of processes that cause material instability may arise from: (i) residual stresses generated as a result of welding operations; (ii) stresses associated with the buildup of corrosion products in the gap between the outer and the inner containers; and (iii) applied stresses from the effect of disruptive events, such as seismic activity, volcanism, faulting, or a combination of these events.

#### 4.3.1.1.3 Quantity and Chemistry of Water Contacting the Waste Packages and Waste Forms

The discussions and technical basis on the quantity and chemistry of water contacting WPs and waste forms abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC’s technical basis for the staff review consistent with the current design and knowledge of site conditions.

The quantity and chemistry of water contacting waste packages and waste forms ISI addresses how much and what type of water interacts with the waste package and waste forms. This ISI is part of the engineered barriers component of the engineered system (Figure 3). The relationships between quantity and chemistry of water contacting WPs and waste forms and other ISIs are illustrated in Figure 6. This ISI is directly linked to the flow paths in the UZ ISI in the UZ flow and transport component of the geosphere.

Radionuclide release rates depend on the quantity of water contacting the WPs and subsequently the waste forms. The quantity of water contacting waste forms is a major factor in determining Radionuclide migration to the accessible environment. The quantity of water contacting the WP is also a major factor in determining the lifetime of the WP. For example, if reasonable assurance could be achieved that the WP remains dry throughout the time period of regulatory interest (i.e., owing to areal mass loading, shielding of the WP from flow, backfill, and others), then the only corrosion failure modes that would be important in performance assessment models would be dry air oxidation and humid air corrosion. Also for this case, the groundwater release would be largely eliminated, even if the WP were to fail through some other failure mechanism (e.g., rockfall) because no liquid water would be flowing through the breached WPs to transport radionuclides to the receptor location. Finally, the availability of water after the repository environment has cooled also affects the potential for microbially induced corrosion. Thus, this ISI addresses that part of the seepage of water into the emplacement drifts which comes into contact with the WPs and waste forms and how that water contacts both the WPs and waste forms.

WP degradation and the radionuclide release rates depend on the chemistry of water contacting the WPs, and subsequently the waste forms. The chemistry of the water contacting WPs plays an important role in determining repository performance. The pH and chloride concentration of the water contacting the WP are important for determining the rate and type of corrosion affecting the container (i.e., uniform or pitting corrosion). The chemistry of water contacting the waste plays an important role in determining the source term for the exposure from the groundwater pathway. For example, release rates and solubilities of radionuclides in water are dependent on pH, carbonate concentration, and oxygen content (i.e., oxidative dissolution of $UO_2$). Distribution coefficients ($K_d$s), which affect the availability of radionuclides for transport in the near-field environment, also depend on pH and other chemical factors (Turner, 1993, 1995). Other processes that depend on water chemistry include alteration of other engineered barrier materials and aqueous speciation of dissolved radionuclides.

The quantity of water that could enter a degraded WP and contact the waste form is a function of the type of corrosion and amount of corrosion (U.S. Nuclear Regulatory Commission, 1999e). The WP could corrode in a manner in which the package acts as a bathtub, such that the water collects in the WP until the water level reaches a hole in the WP, or it could degrade in a manner that only allows water to flow through the WP (U.S. Nuclear Regulatory Commission, 1999e).

The bathtub model is currently the basecase model used in the TPA code. These different WP degradation scenarios could lead to different amounts of water contacting the waste forms. As the WP materials degrade, and alteration minerals are precipitated, the amount of water that can enter or exit the degraded WP may change (U.S. Nuclear Regulatory Commission, 1999d).

Both the composition of the water entering the WP and the water composition inside the WP will evolve as a function of time as a result of THC processes (U.S. Nuclear Regulatory Commission, 1999d). The dissolution rates of the engineered materials and the precipitation rates of the alteration minerals of these materials are a function of temperature (U.S. Nuclear Regulatory Commission, 1999d). As water interacts with the materials inside the WP the water will change in composition.

The following factors relating to this ISI are important for determining the quantity of water that could contact WPs: (i) the presence or absence of backfill, its physical characteristics, moisture retention, and permeability properties (U.S. Nuclear Regulatory Commission, 1999h); (ii) the presence of a drip shield (U.S. Nuclear Regulatory Commission, 1999e); and (iii) the presence of any coatings, such as shotcrete, on walls of tunnels (U.S. Nuclear Regulatory Commission, 1999h). The change in the engineered barriers design concept to one where there is a titanium drip shield changes the assessment of that portion of the seepage that comes into contact with the WP (U.S. Nuclear Regulatory Commission, 1999e).

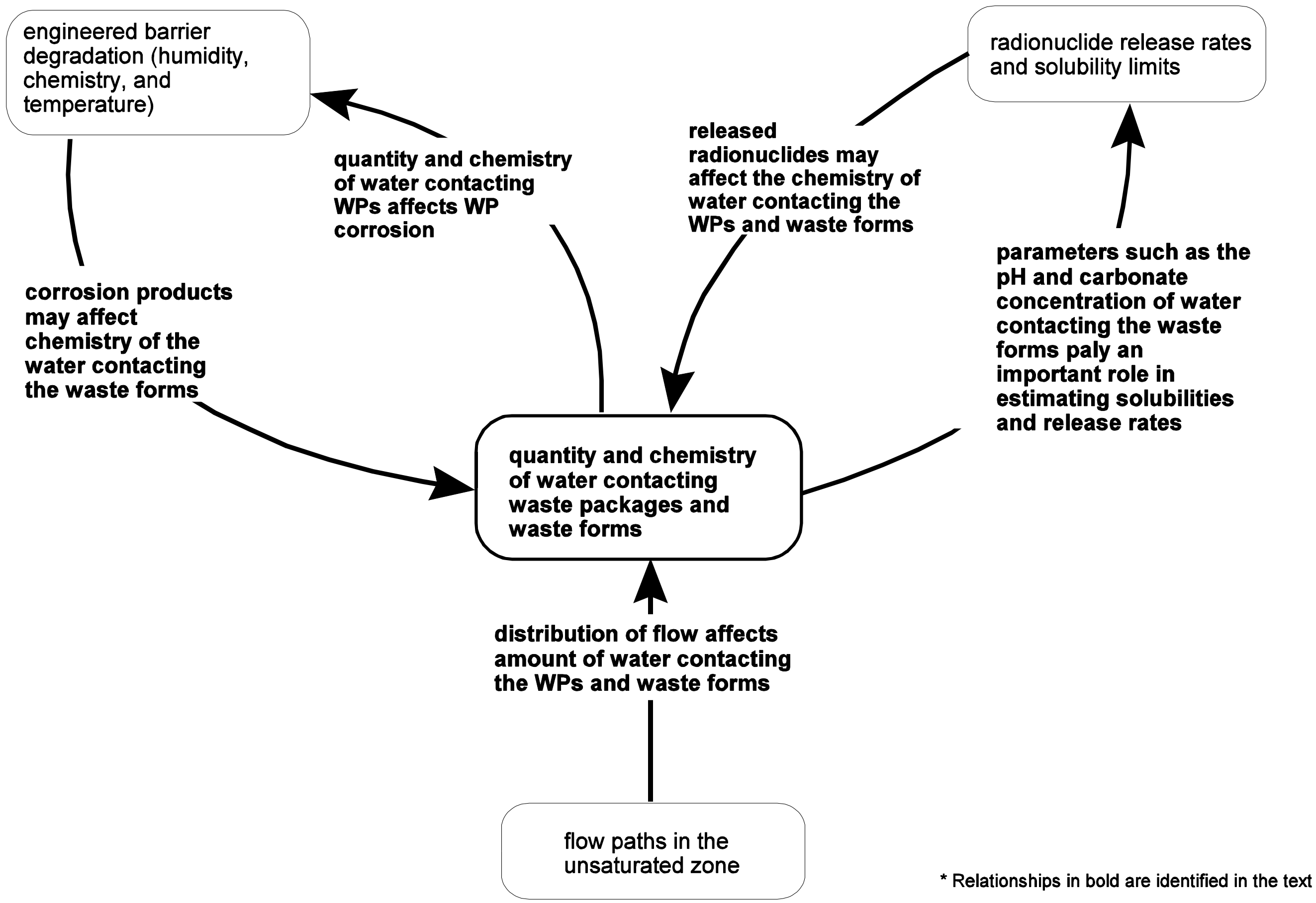



**Figure 6. Diagram of the relationships between "quantity and chemistry of water contacting waste packages and waste forms" and other integrated subissues**

In addition, several factors affect the quantity of water that could contact the waste forms: (i) the quantity of water contacting the WP (U.S. Nuclear Regulatory Commission, 1999e); (ii) WP materials and their rates and modes of degradation (U.S. Nuclear Regulatory Commission, 1999e); (iii) the timing, during the postclosure period, of water contact with WPs (U.S. Nuclear Regulatory Commission, 1999j); (iv) the geometry of WP failures (e.g., patches or pits) that determines the pathway for water entry and exit for the WP (U.S. Nuclear Regulatory Commission, 1999e); (v) the degradation modes and rates for spent nuclear fuel (SNF) cladding (U.S. Nuclear Regulatory Commission, 1999e); and (vi) formation of WP material degradation products that could divert water from entering the WP or plug water release pathways (U.S. Nuclear Regulatory Commission, 1999d).

Finally, several factors related to this ISI affect the chemistry of water that could contact the waste packages and waste forms: (i) interactions between thermal fluids and the engineered barriers materials, including dissolution of the backfill, drip shield, roof support materials, WP materials, cladding, and waste forms, and precipitation of alteration minerals of the engineered materials (U.S. Nuclear Regulatory Commission, 1999d); (ii) evaporative concentration of fluids contacting the waste package and waste forms (U.S. Nuclear Regulatory Commission, 1999j); (iii) microbial activity (U.S. Nuclear Regulatory Commission, 1999d); and (iv) radiolysis (U.S. Nuclear Regulatory Commission, 1999e).

The quantity and chemistry of water contacting the WP and waste forms are also important to the degradation of the EBS materials and the release of their constituents into the geosphere. This ISI is also potentially important to system performance because of the influence on flow paths in the UZ and radionuclide transport (RT) in the UZ.

The materials dissolved and released from the EBS depend on the quantity and chemistry of water. These dissolved materials could be precipitated onto flow surface in the rocks in the UZ beneath the repository. The precipitation of these alteration minerals could affect both the amount of flow that can enter the matrix and the transport of radionuclides in the UZ. For example, many of the metal oxides that could precipitate have strong sorptive characteristics (e.g., Turner, 1995).

The amount and distribution of water flowing through the repository are key technical components affecting total system performance (Electric Power Research Institute, 1998). The models used to describe the quantity of water contacting the WP and waste forms are important to total system performance (U.S. Nuclear Regulatory Commission, 1999b; Mohanty, et al., 1999; U.S. Department of Energy, 1998a).

The quantity of water contacting WPs plays an important role in determining the lifetime of the WP and the release rates of radionuclides after the WPs have failed (U.S. Nuclear Regulatory Commission, 1999e). Current models for predicting WP lifetimes have several regimes for the predominant failure mechanism based on the RH of the near-field environment (U.S. Nuclear Regulatory Commission, 1999e, also see Section 4.3.1.1.1). For several mono-layers of water to sorb to the surface of the WP, the RH of the repository drift surrounding the WP must be greater than about 60 to 65 percent (Mohanty, et al., 1997). As a result, liquid water contacting the WPs can initiate aqueous corrosion (U.S. Nuclear Regulatory Commission, 1999e, also see Section 4.3.1.1.1). However, if gravity-driven dripping of water from thermal reflux onto WPs occurs, local conditions on the WP would exceed the RH of the repository and corrosion of a WP could ensue (U.S. Nuclear Regulatory Commission, 1999e).

The release rates of radionuclides are also dependent on the quantity of water contacting the waste forms. Radionuclide release is usually divided into two regimes; a release-rate-limited regime and a solubility-limited regime. When a large flow of water contacts waste forms such that not all the water can be saturated with a given radionuclide, the rate of release of the radionuclides is dissolution limited. In this case, radionuclide releases in performance assessment are usually calculated by multiplying the WP radionuclide inventory by a maximum fractional release rate for that radionuclide (Mohanty, et al., 1997). In the solubility-limited regime, there is sufficient radionuclide release to saturate the water with a given radionuclide. In either case, it is necessary to estimate the quantity of water contacting the waste. Maximum fractional release rates and radionuclide solubilities are discussed in Section 4.3.1.1.4 (also see U.S. Nuclear Regulatory Commission, 1999e). Properties of the repository system that may affect the amount of water contacting WPs and subsequently the waste forms include the presence (or absence) of backfill, which may divert water away from the WP; funneling of water to discrete fractures that may or may not intersect the WP; infiltration rates of water exceeding the hydraulic conductivity of the rock causing dripping in the drift; thermal reflux of water; and the amount and location of water dripping onto the WPs.

The chemistry of the water contacting WPs also plays an important role in determining repository performance (U.S. Nuclear Regulatory Commission, 1999e). As discussed previously in this section and earlier in Section 4.3.1.1.1, the pH and chloride concentration of the water contacting WP are important for determining the rate and type of corrosion affecting the container (e.g., uniform or pitting corrosion). In addition, pH and the carbonate concentration affect the dissolution rate of the commercial SNF (U.S. Nuclear Regulatory Commission, 1999e,d). Also, parameters such as pH and the redox state of the water are important for estimating radionuclide solubilities in water, as some species have markedly different solubilities in oxidizing versus reducing environments (e.g., $U_3O_8$ versus $UO_2$), and aqueous solubility and speciation are strong functions of pH. In previous DOE TSPAs (Wilson, et al., 1994), uncertainties in YM groundwater pH are characterized as providing one of the major sources of uncertainty for predicting radionuclide solubilities. Distribution coefficients for radionuclides between the aqueous phase and the host rock minerals of the repository block and other parts of the repository system are also dependent on pH and other water chemical characteristics (Turner, 1993, 1995; U.S. Nuclear Regulatory Commission, 1999d).

#### 4.3.1.1.4 Radionuclide Release Rates and Solubility Limits

The discussions and technical basis on the radionuclide release rates and solubility limits abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The radionuclide release rates and solubility limits ISI addresses the release of radionuclides from the EBS to the geosphere. This ISI is part of the engineered barriers component of the engineered system (Figure 3). Figure 7 is a diagram illustrating the relationships between "radionuclide release rates and solubility limits" and other ISIs.

Radionuclide release from the EBS will depend on several processes: the dissolution of the waste forms, the contact of the waste form with liquid water, and the solubility limit of radionuclides and other components of the decomposed fuel, transport in liquid water, interaction with engineered barrier materials, and potentially, nuclear criticality. The waste form will begin to decompose once it comes into contact with air, water vapor, and liquid water. However, transport of radionuclides away from the waste form to the geosphere generally requires a liquid water pathway. radionuclides would be released from the waste form to the water within the WP at a rate controlled by either (i) the rate of waste form decomposition (i.e., congruent dissolution); (ii) the rate of dissolution of secondary mineral into which the radionuclides have become incorporated (e.g., schoepite uranyl-hydrate); or (iii) the solubility of the radionuclides themselves. The rates of dissolution and the secondary minerals that could form are different for the different waste forms (e.g., SNF and glass). The rate of water flow through the WP and concentration of radionuclides in the WP waters ultimately controls the release rate from the WP (although molecular diffusion might be relatively important in a situation where flow rates are small). Solubility of radionuclide elements might limit concentrations in WP water if release of radionuclides from the waste form would result in concentrations higher than the solubility limit (although colloid precipitation is also a possibility, especially for the glass waste form). Once radionuclides are released from the WP into the waste emplacement drifts, interaction with other engineered components could affect the release of radionuclides to the geosphere. Near-field coupled THC processes will affect the environment for radionuclide release from the EBS. Both the composition of the water entering the WP and the water composition inside the WP will evolve as a function of time as a result of THC processes. As water interacts with the materials inside the WP it will change in composition. The evaluation of the chemical composition of the water in the WP is discussed in Section 4.3.1.1.3 of this IRSR, Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms. The dissolution rates of the host rock and engineered materials, and the precipitation rates of the alteration minerals of these materials are a function of temperature. In addition, as the materials degrade and alteration minerals are precipitated, the amount of water that can enter or exit the degraded WP may change. The degradation rate of the Zircalloy cladding that surrounds the SNF and the dissolution rates of both the SNF and glass waste forms, are strong functions of the chemistry of the water. Other engineered materials in the emplacement drifts, including backfill, will also be affected by coupled THC processes. The coupled THC processes could affect both hydraulic properties of the flow path from the WP into the geosphere and the sorptive properties of the engineered materials.

The following are the main processes and important factors that compose this ISI. For SNF, several components are important: (i) SNF types; (ii) radionuclide inventory and distribution in the fuel; (iii) dry oxidation of the SNF and its effects on subsequent performance in aqueous environment; (iv) dissolution in aqueous environment; (v) solubility of radionuclides; (vi) secondary mineral formation and coprecipitation; (vii) formation of colloids; (viii) cladding performance; (ix) conceptual models for release from WPs; and (x) nuclear criticality within the WP. For the glass waste form several components are important: (i) HLW glass dissolution processes; (ii) formation of secondary minerals; (iii) effects of colloids and microbes; and (iv) conceptual models for release from the WPs. Finally, the description of the release of radionuclides to the geosphere, once they are released from the WPs must consider: (i) the hydrologic and chemical characteristics of the engineered materials such as backfill; (ii) the sorptive characteristics of the engineered materials beneath the WPs; (iii) changes in both the sorptive and hydraulic characteristics of engineered materials beneath the WPs due to coupled THC processes; and (iv) nuclear criticality within the emplacement drift, external to the WP.

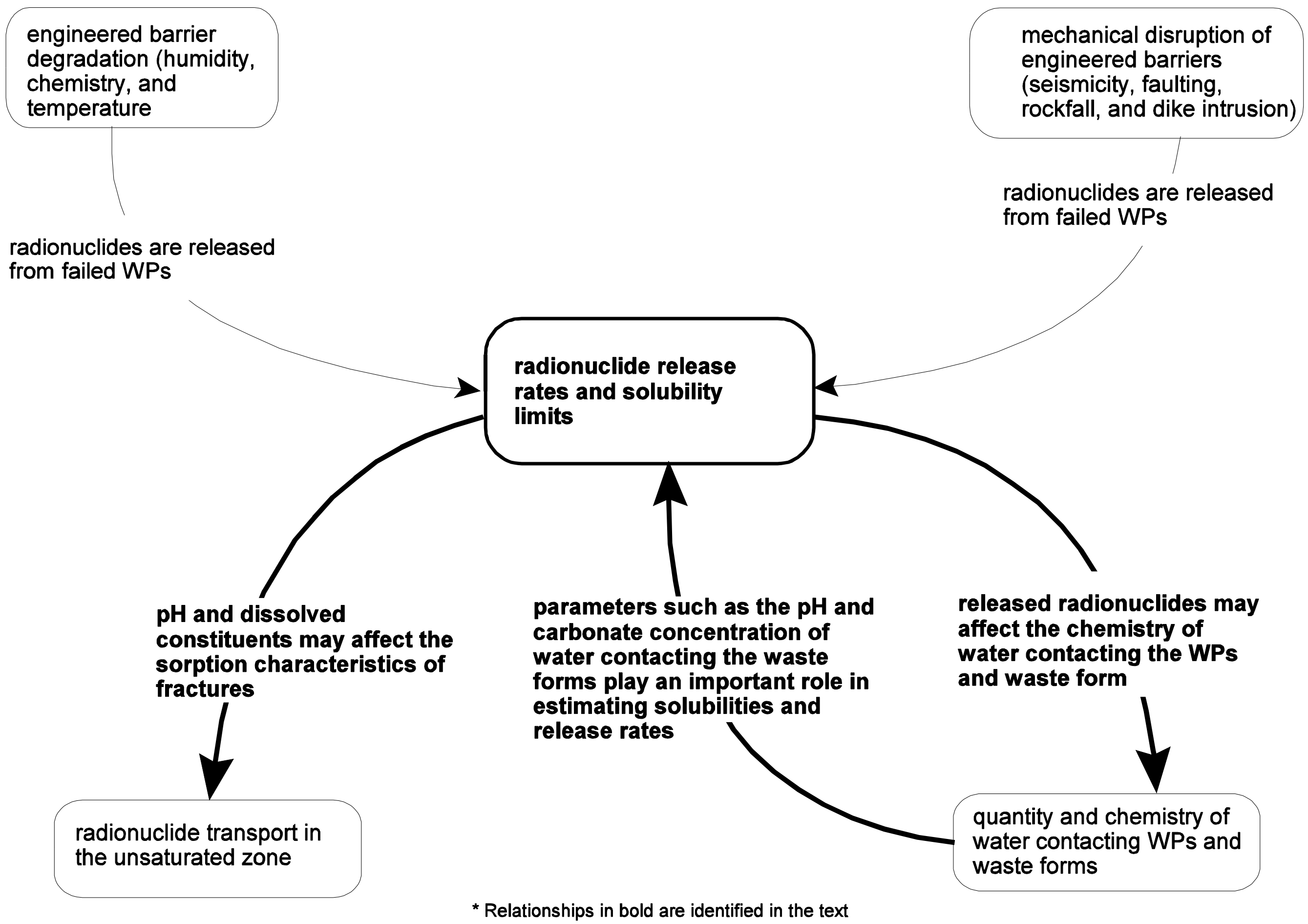



**Figure 7. Diagram of the relationships between "radionuclide release rates and solubility limits" and other integrated subissues**

The degradation of the EBS materials and the release of their constituents into the geosphere also potentially are important to system performance because of the influence on flow paths in the UZ and RT in the UZ.

The dissolved materials, primarily metals, released from the EBS could be precipitated onto flow surfaces in the rocks in the UZ beneath the repository. The precipitation of these alteration minerals could impact both the amount of flow that can enter the matrix and the transport of radionuclides in the UZ. Many of the metal oxides that could precipitate have strong sorptive characteristics.

The rate of release of uranium and other species from breached WPs is controlled by a series of processes, such as transport of oxidants and flux of water, oxidative dissolution of SNF, uranyl mineral precipitation, uranyl mineral dissolution or transformation, and transport of radionuclides, and is affected by the condition of the fuel cladding. The waste dissolution rate and elemental solubilities are key technical components affecting total system performance (Electric Power Research Institute, 1998; U.S. Department of Energy, 1998a). The models used to describe waste form dissolution and the extent to which cladding can protect the SNF from contact with water are important to total system performance (U.S. Nuclear Regulatory Commission, 1999b; Mohanty, et al., 1999; U.S. Department of Energy, 1998a). Four different SNF dissolution models, each one constructed based on assumptions of the chemistry contacting the waste form and different assumptions concerning the presence or absence of secondary uranium minerals, predict differences in dose at 10,000 years that vary by one order of magnitude or more (Mohanty, et al., 1999).

Examples of possible important physical phenomena and couplings with other ISIs are (see Figure 7):

- Parameters such as the pH and carbonate concentration of water contacting the waste form play an important role in estimating solubilities and release rates. Released RNs may affect the chemistry of water contacting the WPs and waste forms (quantity and chemistry of water contacting WPs and waste forms).

- pH and dissolved constituents may affect the sorption characteristics of fractures (retardation in fractures in the UZ).

- Seepage into the emplacement drifts affects the chemistry of the environments on the waste package (flow paths in the UZ).

The release of radionuclides from the WP and engineered barriers is dependent on, for example, the concentration of radionuclides contained in the water of breached WPs (U.S. Nuclear Regulatory Commission, 1999e). Radionuclide release from the SNF into water contacting the waste forms is in turn dependent on either the solubility of the individual radionuclide or the solubility of the waste matrix. The radionuclide solubilities represent the upper limit for individual radionuclide concentrations in WP water and depend on conditions in the near-field environment (U.S. Nuclear Regulatory Commission, 1999d).

A typical approach to analyze the radionuclide release rates and solubility limits is as follows. The solubility of the waste matrix, when combined with an amount of water in contact with the waste, determines the annual fraction of radionuclide inventory released to WP waters (U.S. Nuclear Regulatory Commission, 1999e). If annual releases of RNs to WP water dictate concentrations greater than the solubility limits would allow, radionuclide concentrations are truncated to the solubility limits (U.S. Nuclear Regulatory Commission, 1999e). In this manner, both radionuclide solubilities and the waste matrix solubility (determining the release rate for radionuclides) contribute to estimates of repository performance.

Performance assessment models can use what is referred to as a “bath tub” model, where a volume of water is stored within a failed WP (Mohanty, et al., 1997), or a “flow-through” model (U.S. Nuclear Regulatory Commission, 1999k) where water does not collect in the WP. Advective and diffusive releases from the WP are estimated; both of which require estimation of time-dependent radionuclide concentrations in the water contained within the WP. In advective release, the rate at which water exits the WP is multiplied by the radionuclide concentration to obtain an exit rate for radionuclides from the WP (U.S. Nuclear Regulatory Commission, 1999e). In diffusive release, the concentration of radionuclides in WP waters is used to estimate the concentration gradient necessary for calculating the diffusive flux of radionuclides from the WP. To estimate time-dependent radionuclide concentrations inside a breached WP, alternative expressions for the dissolution rate of radionuclides in the SNF are used (U.S. Nuclear Regulatory Commission, 1999d,e). Then, a mass balance is performed for the radionuclide concentration in the WP water. The total release rate of radionuclides to WP waters is the dissolution rate multiplied by the radionuclide inventory in the WPs (U.S. Nuclear Regulatory Commission, 1999e).

The radionuclides exiting the WP will travel through the material that supports the WP and lines the floor of the emplacement drifts (U.S. Nuclear Regulatory Commission, 1999d). These materials could sorb the radionuclides and decrease the release rate from the EBS depending on if it will matrix flow or fracture flow through the materials (U.S. Nuclear Regulatory Commission, 1999d). The physical properties and sorptive capabilities of these materials may change as a result of coupled thermal-hydrologic-chemical (THC) processes (U.S. Nuclear Regulatory Commission, 1999d).

Both the radionuclide and waste matrix solubilities are strongly dependent on the near-field environment (i.e., temperature and chemistry of water contacting waste) (U.S. Nuclear Regulatory Commission, 1999d). The chemistry of water contacting the waste affects the oxidation state in which radionuclides exist and ultimately, the solubility and release rate of the radionuclides (U.S. Nuclear Regulatory Commission, 1999d). In an oxidizing environment, such as the YM repository setting, $UO_2$ in the SNF may ultimately exist as $U_3O_8$ or $UO_3$, which have markedly different solubilities from $UO_2$ (U.S. Nuclear Regulatory Commission, 1999d). Similarly, Tc is generally considered soluble under oxidizing conditions but relatively insoluble under reducing conditions (U.S. Nuclear Regulatory Commission, 1999d). Solubility limits are also sensitive to parameters dictated by the chemistry of the near-field environment. For example, a model for the dissolution rate of SNF (and hence radionuclides contained in the fuel) contains equations with terms dependent on pH, carbonate concentration, temperature, and Si and Ca concentrations (U.S. Nuclear Regulatory Commission, 1999e).

Secondary minerals could precipitate on or near the SNF as a result of homogeneous reaction between uranyl species and the near-field environment (U.S. Nuclear Regulatory Commission, 1999d). The secondary minerals may mitigate radionuclide release by partially blocking the SNF surface from directly coming in contact with the water (U.S. Nuclear Regulatory Commission, 1999e). Periodic spallation of the dissolution product could occur exposing a fresh surface of SNF for further dissolution (U.S. Nuclear Regulatory Commission, 1999e). Drip test results using J-13 Well water indicate that key nuclides, such as Np and Cs, can be concentrated at the surface of the SNF in the secondary mineral deposits (U.S. Nuclear Regulatory Commission, 1999e). Even though the SNF surface may be masked by secondary minerals, consideration should be given to the easy access of some nuclides to the water contacting the SNF (U.S. Nuclear Regulatory Commission, 1999e).

In spite of a small volumetric inventory of HLW glass, its contribution to performance assessment could be significant if the radionuclide release rate is higher than the radionuclide release rate from SNF (e.g., radionuclide release in colloidal form or pulse release of radionuclides from the hydrated surface layer) (U.S. Nuclear Regulatory Commission, 1999e). Formation of secondary minerals could affect the long-term release rate from glass. The secondary phases on the surface of the glass waste could be released as colloids that could lead to sudden increase in actinide concentration in the near-field environment (U.S. Nuclear Regulatory Commission, 1999e). Microbes can also change the solubilities of radionuclides by the increased production of organic acids (U.S. Nuclear Regulatory Commission, 1999d).

In summary, radionuclide release from the WP might be controlled by solubility limits of radionuclide elements or the products of waste form decomposition. Unless colloids form, the radionuclide solubilities represent the upper limit for radionuclide concentration in the WP water and depend on parameters describing the near-field environment (U.S. Nuclear Regulatory Commission, 1999d).

### 4.3.2 Geosphere

From the standpoint of transport of radionuclides to a receptor group, the geosphere is composed of several subsystems: the UZ, the SZ, and direct release into the atmosphere. To evaluate the contribution that the geosphere makes to meeting the system performance objective, the current approach is to focus on the intermediate calculations that provide the distribution of release rates, as a function of time, of radionuclides to the water table below the proposed repository and at the receptor location.

#### 4.3.2.1 Unsaturated Zone Flow and Transport

In this section, the descriptions and technical basis for the acceptance criteria and review methods for the three key elements under the UZ flow and transport abstraction, as identified in Figure 3 (i.e., climate and infiltration, flow paths in the UZ, and radionuclide transport in the UZ), are discussed. The key abstractions were derived from staff experience with previous and current performance assessment activities, reviews of DOE's TSPAs, sensitivity studies performed at the process and system levels, and reviews of DOE's hypotheses in its Repository Safety Strategy. Further, these key abstractions represent the essential factors to be considered in demonstrating the UZs capability to improve total system performance.

##### 4.3.2.1.1 Climate and Infiltration

The discussions and technical basis on the climate and infiltration abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The climate and infiltration ISI addresses the near-surface hydrologic processes, such as precipitation, temperature, climate change, and present-day infiltration. Infiltration is strongly correlated with the amount of water reaching the repository horizon which significantly influences the subsequent transport of RNs to the water table in unsaturated fractured rock. This ISI is derived from the UZ component of the geosphere subsystem (Figure 3). The relationships between climate and infiltration and other ISIs are illustrated in Figure 8.

Present-day infiltration is an important factor in the isolation of the HLW within a proposed geologic repository at YM. It should be reasonably understood so as to provide the initial conditions for projecting future hydrologic changes, because the Earth's climate could change significantly during the time that wastes will remain hazardous. The study of climate change involves both natural and anthropogenic components. Long-term natural variations in climate are clearly seen in the paleoclimatic record of the last 500 k year. Five glacial/interglacial cycles occurred during that interval, each lasting roughly 100 k year. Climate controls the range of precipitation that, in part, controls the rates of infiltration, percolation, and seepage flux through the repository. Changes in present-day infiltration will likely induce other changes, such as regional fluctuations in the elevation of the water table.

Water table rise would reduce the thickness of the UZ below the repository. Therefore, future changes in climate that alter infiltration from present-day rates could also reduce the effectiveness of the UZ to work as a barrier and isolate waste.

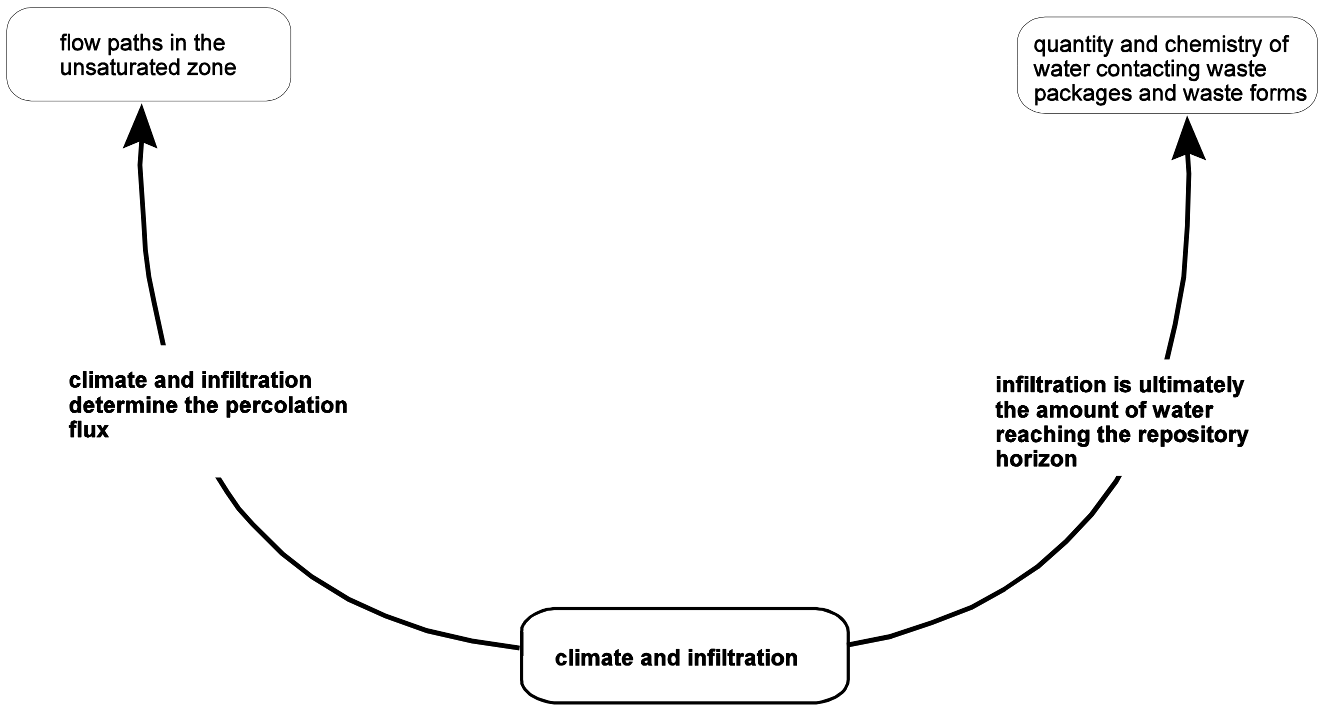
The liquid-water flux that has moved beyond the zone of evapotranspiration and remains in the rock is infiltration. It is the fraction of precipitation that has penetrated the ground surface and moved just below the zones of evaporation and transpiration (influence of plant roots). Within a given drainage basin, there is both temporal and spatial variability of infiltration capacity. Spatial variations occur because of differences in soil types, thicknesses, and vegetation. Infiltration incorporates the surface and near-surface processes of precipitation, overland flow, heat flux, and evapotranspiration. These processes impact groundwater flow in the colluvial and alluvial sediments as well as the top few meters of bedrock. Although there may be evaporation from the fracture system down to the PTn and further, especially as suggested by the high air permeability in the TCw, the amount is not considered significant with respect to the mean annual infiltration (MAI).

Climate models strongly affect performance predictions by their influence on precipitation and evapotranspiration, which have the dominant effect on infiltration and are important to performance in the TPA code. Infiltration is a dominant factor in determining the quantity of water flowing past the WPs, which provides the mechanism for mobilization of dissolved RNs moving through the UZ. Magnitude and timing of climate change are thus important. Factors controlling predicted repository performance are the magnitude of precipitation changes and the assumed starting infiltration rate; changes in infiltration due to temperature change are less important. For TPA purposes, net infiltration fluxes are assumed to be numerically equivalent to deep percolation fluxes.

The following are examples of possible important physical phenomena and couplings with other ISIs (see Figure 8):

- Infiltration is strongly correlated with the amount of water reaching the repository horizon (quantity and chemistry of water contacting WPs and waste forms).

- Climate change and infiltration determines the percolation flux (flow paths in the UZ).




* Relationships in bold are identified in the text

**Figure 8. Diagram of the relationships between "climate and infiltration" and other integrated subissues**

The current NRC model assumes infiltrating waters proceed through the repository horizon to the water table with negligible evaporation and lateral diversion. At and below the repository horizon, deep percolation is assumed to adjust quickly to climatic variation. Both Mean Annual Precipitation (MAP) and Mean Annual Temperature (MAT) are calculated using past glacial cycles with random perturbations from the mean at every 100- or 500-year interval. The magnitude of change in MAP and MAT under full glacial conditions is sampled stochastically.

The current MAI, which is assumed to be equivalent to deep percolation, is sampled stochastically. Subsequent changes in MAI due to changes in MAP and MAT are calculated using a transfer function (regression equation), which is generated from the results of numerous offline one-dimensional (1D) simulations, incorporating the influences of soil depth, elevation, and insolation.

#### 4.3.2.1.2 Flow Paths in the Unsaturated Zone

The discussions and technical basis on the flow paths in the UZ abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The flow paths in the UZ ISI addresses the distribution of moisture flow in unsaturated fractured rock and seepage into the emplacement drifts. This ISI is part of the natural barrier system and derived from the UZ component of the geosphere subsystem (Figure 3). The relationships between flow paths in the UZ and other ISIs are illustrated in Figure 9.

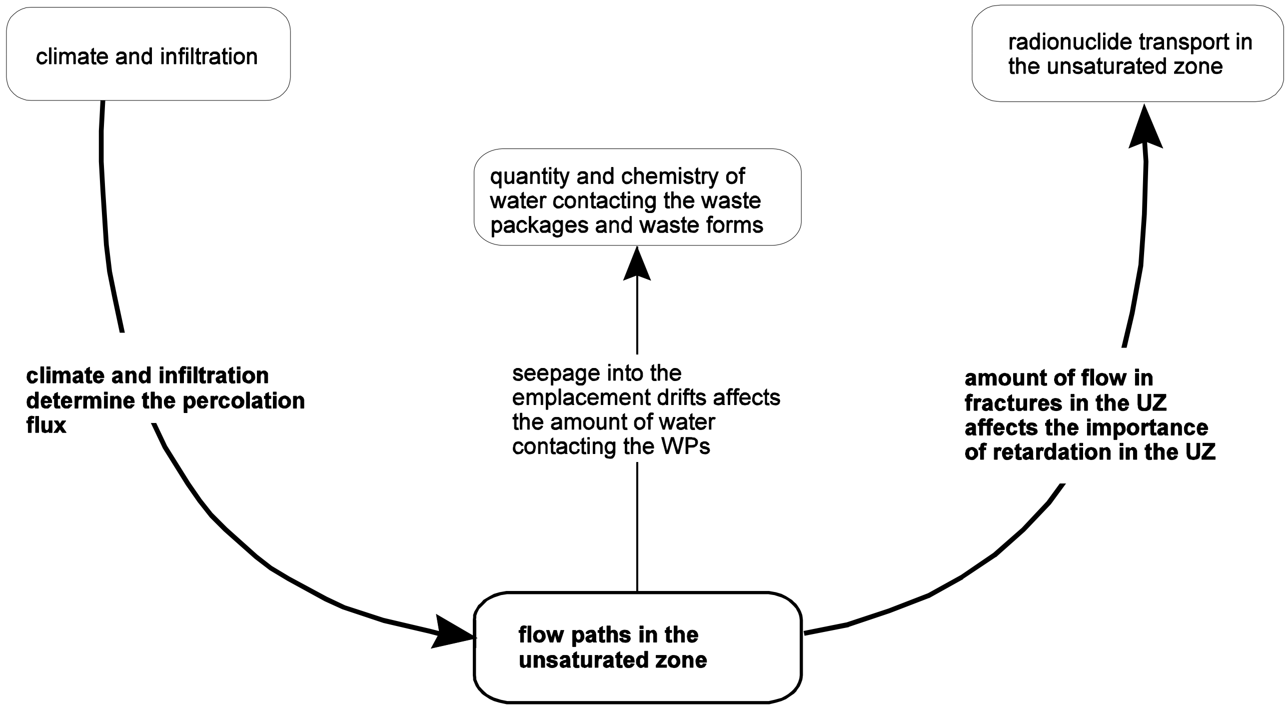
The hydraulic characteristics of flow in the UZ will depend on the geometric characteristics of individual fractures and faults (e.g., size, aperture, and roughness), fracture populations, fracture fillings, and associated deformation along fractures or fault zones. Flow (i.e., liquid-water flux) in the UZ from the ground surface to the repository horizon and from the repository to the groundwater table occurs in both the fractures and the rock matrix. The fraction of water flowing through the rock matrix is dependent on total percolation flux, which is the liquid-water flux below the zone of infiltration that moves downward through the UZ. The percolation flux at the repository horizon depends on the precipitation and temperature of the modeled climate, the estimate of infiltration for that climate, and the spatial and temporal movement of water through the welded and nonwelded tuffs above the repository. Percolation flux at the repository directly impacts the distribution and magnitude of seepage into drifts. If the capacity of the rock matrix to conduct water is larger than the total infiltration flux, the classical view is that little or no water will flow in fractures because capillary forces will retain infiltrating water in the rock matrix. When the flow of infiltrating water in the UZ approaches or exceeds the matrix flow capacity, an increasingly greater fraction of flow is conducted in fractures. Subsurface flow predominantly through the matrix would likely limit the net water flux into repository drifts owing to capillary-barrier effects. However, heterogeneity in matrix properties at the drift scale may enable flow to locally exceed matrix capacity even when flow is predominantly through the matrix, thereby making more likely the possibility of liquid water entering the drifts.

The percolation rate at the repository horizon is generally assumed uniform in time and equal to infiltration. Factors such as soil cover, evapotranspiration, and type of bedrock determine the quantity of infiltration, which occurs as pulses following precipitation. Flow paths also may be focused by heterogeneities such as fracture and fault zones (U.S. Nuclear Regulatory Commission, 1999h). Although infiltration is not spatially or temporally uniform, the wetting pulses are attenuated en route to the repository; and become more uniform spatially and temporally.

Thus, percolation is assumed uniform at the repository horizon in all YM PAs. The paintbrush nonwelded-tuff (PTn) layer above the repository level is thought to be especially effective in damping and spreading infiltration pulses, even those occurring within fractures. All DOE, NRC, and EPRI YM TSPAs to date have assumed that fluxes below the PTn layer only change during glacial time scales, as driven by changes in the climate (e.g., current versus pluvial climate). Evidence of fast pathway movement as suggested by geochemical signals, however, implies that focused infiltration, fracture pathways through the PTn, and heterogeneities within the PTn may contribute to episodic pulses of flow to the repository horizon and below. Determination of the portion of flow that moves in episodic fashion along the fast pathways relative to the entire UZ flow is problematic.

Near-field THC processes may affect the distribution of mass flux between the fracture and matrix. Thermally altered zeolitic horizons, resulting from the dehydration of zeolitic minerals, may create new fractures and widen existing fractures. This process may lead to an increase in fracture flow. The dissolution and transport of mineral constituents such as silica and calcium, followed by precipitation during evaporation, could also modify the permeability distribution near the repository horizon. Thermally driven water may affect the fracture and matrix hydraulic pathways in vertical and near-vertical fractures due to gravity-driven refluxing. Additionally, direct faulting or ground shaking from earthquakes could perturb the fracture and fault network and significantly alter existing groundwater flow systems. Dilation of fractures could concentrate seepage within the drifts, focus and speed groundwater flow from the repository to the groundwater table, and even shift the present groundwater potentiometric surface beneath YM to bring the groundwater table closer to the base of the repository. Faulting, earthquakes, and igneous intrusion could also impact downstream groundwater flow in the fractured tuff and valley-fill aquifers. These processes could lead to greatly reduced groundwater travel times and concentrations of radionuclides within the tuff and valley-fill aquifers.

The quantity of water that could drip (i.e., seep) from the ceiling and walls of a drift is usually determined for ambient conditions (U.S. Nuclear Regulatory Commission, 1999h). However, for the YM repository, the construction of the drifts and the emplacement of heat-producing WPs will cause coupled THMC processes to affect the amount of water that could seep into the drifts and contact the WPs (U.S. Nuclear Regulatory Commission, 1999h). Coupled TH processes, such as the boiling of water, condensation of vapor, and gravity drainage of the condensed water back to the drift (these processes are known as thermal reflux), are an important modifier to the amount of water that could seep into the drifts (U.S. Nuclear Regulatory Commission, 1999j). Near-field coupled THC processes will affect both the quantity and chemistry of water entering the emplacement drifts (U.S. Nuclear Regulatory Commission, 1999d). The dissolution rates of the host rock and engineered materials and the precipitation rates of the alteration minerals of these materials are a function of temperature (U.S. Nuclear Regulatory Commission, 1999d). As the host rock is geochemically altered, the flow properties of the rock could change due to volume changes as minerals dissolve and new minerals precipitate. This could change the amount and spatial distribution of seepage into emplacement drifts (U.S. Nuclear Regulatory Commission, 1999j). Coupled TM and TMH processes could also change the amount of seepage predicted for isothermal conditions (U.S. Nuclear Regulatory Commission, 1999g). Modeling results indicate that the amount of water that can be diverted around the emplacement drift via capillarity is a strong function of the surface roughness of the drift (U.S. Nuclear Regulatory Commission, 1999h). Coupled TM processes can cause drift degradation (U.S. Nuclear Regulatory Commission, 1999g) and could lead to larger amounts of seepage than would be predicted for a smooth drift (U.S. Nuclear Regulatory Commission, 1999j). In addition, differential opening and




* Relationships in bold are identified in the text

**Figure 9. Diagram of the relationships between "flow paths in the unsaturated zone" and other integrated subissues**

closing of fractures from TM effects will change the hydraulic conductivity of fractures (U.S. Nuclear Regulatory Commission, 1999g).

The following factors related to this ISI are important for determining the seepage into the emplacement drifts: (i) fracture geometry, frequency, coatings, intersections, and degree of heterogeneity (U.S. Nuclear Regulatory Commission, 1999f,h); (ii) hydraulic properties of fractures, including heterogeneity of properties (U.S. Nuclear Regulatory Commission, 1999h); (iii) percolation flux at the drift and its spatial and temporal variability (U.S. Nuclear Regulatory Commission, 1999h); (iv) the diversion of matrix flow and dripping from fractures at the crown of the drift (U.S. Nuclear Regulatory Commission, 1999h); (v) flow focusing toward or diversion away from drifts (U.S. Nuclear Regulatory Commission, 1999h,j); (vi) the percolation threshold, below which no seepage into the drift will occur; (vii) the effect of cavity wall roughness (U.S. Nuclear Regulatory Commission, 1999j); (viii) the effects of coupled thermal-hydrologic processes including, the extent of rock dry out surrounding the drifts, penetration of the boiling isotherm by water flow down a fracture leading to dripping into a drift during times when repository and WP temperatures are predicted to be above boiling, and the extent and duration of thermal reflux (U.S. Nuclear Regulatory Commission, 1999j); (ix) the TM effects on drift geometry (U.S. Nuclear Regulatory Commission, 1999g); (x) the coupled TMH effects on fracture hydraulic properties (U.S. Nuclear Regulatory Commission, 1999g,j); and (xi) the coupled THC processes leading to changes in the hydraulic properties of fractures (U.S. Nuclear Regulatory Commission, 1999d).

Factors relating to this ISI affect the chemistry of the water entering the emplacement drifts: interactions between thermal fluids and the host rock, including dissolution of host minerals and precipitation of alteration minerals (U.S. Nuclear Regulatory Commission, 1999d) and changes in the gas composition due to coupled THC processes (U.S. Nuclear Regulatory Commission, 1999d).

Flow paths in the UZ are potentially important to system performance because of the influence on RT in the UZ and SZ and the quantity of water contacting the WP and waste forms

Deep percolation fluxes, resulting from infiltration of meteoric waters are important to isolation performance of the proposed repository (Wescott, et al., 1995; U.S. Department of Energy, 1998a; Kessler and McGuire, 1996). Partitioning of deep percolation flux into matrix and fracture flow is important because water flowing in the rock matrix is far less likely to drip onto a WP, and RT through the rock matrix is slow and subject to significant sorption on mineral surfaces. NRC sensitivity analyses have shown that the simulated performance of the proposed repository (for the 10,000-year time period of interest) was strongly influenced by a factor intended to represent flow focusing or diversion by the natural system (Mohanty, et al., 1999). This factor is derived, in part, within the flow paths in the UZ ISI.

An ongoing peer review of the DOE drift seepage approach has identified inadequacies in the data, experiments used to collect the data, the models used to describe the seepage process, and the methods used to abstract seepage into performance assessment (Hughson, 1999; Drift Seepage Peer Review Panel, 1999). The potential for gravity-driven refluxing during the thermal period and its importance for adequately describing WP performance has been presented to DOE (Bell, 1997; U.S. Nuclear Regulatory Commission, 1999j; Drift Seepage Peer Review Panel, 1999). The amount and distribution of water flowing through the repository are key technical components affecting total system performance (Electric Power Research Institute, 1998). The models used to describe seepage are important to total system performance (U.S. Nuclear Regulatory Commission, 1999b; Mohanty, et al., 1999; U.S. Department of Energy, 1998a).

The following are examples of possible important physical phenomena and couplings with other ISIs (see Figure 9):

- Seepage into the emplacement drifts affects the amount of water contacting the waste packages (quantity and chemistry of water contacting the WPs and waste forms).

- Amount of flow in fractures in the UZ affects the importance of retardation in fractures (retardation in the UZ).

Flow in the UZ from the ground surface to the repository horizon and from the repository to the groundwater table is predominantly in fractures in both the welded and nonwelded units. Significant variability of flow and transport pathways and travel times is expected to occur at YM due to the natural heterogeneity, stratification, alteration, fracturing, and other characteristics of the site. Given the matrix permeability values and assuming a unit hydraulic gradient, groundwater flowing only in the matrix would move sufficiently slowly that it would take many tens of thousands of years for shallow infiltration to go through the repository horizon and arrive at the SZ. In contrast, both geochemical evidence and transient-flow modeling have suggested that a significant amount of groundwater flows in the fracture system and that these fluxes are higher than those in the matrix. Fracture flow tends to be orders of magnitude faster than matrix flow, with water passing through a layer in a matter of decades or less. Fracture flow likely occurs only when the percolation exceeds the saturated hydraulic conductivity of the matrix; when flow occurs, it is assumed the interconnected fractures are capable of conducting the remaining flow.

Current modeling of groundwater flow through the UZ indicates, that on the time scale of repository performance, travel times through the fractures are almost negligible. Thus, determination of fracture versus matrix flow is considered the most important aspect of the UZ flow because of the fast fracture flows and the retardation of RNs within fractures is generally considered to be much smaller than retardation in the matrix. Conservatively, flow can be considered to be downward toward the water table with no lateral diversion. Lateral diversion near perched water may divert flow and result in longer travel times to the water table.

The THC processes that should be evaluated to determine their potential importance to repository include (i) zeolitization of volcanic glass, which could affect flow pathways; (ii) precipitation of calcite and opal on the footwall of fracture surfaces and the bottoms of lithophysal cavities, which indicates gravity driven flow in open fractures that could affect permeability and porosity; and (iii) potential dehydration of zeolites and vitrophyre glass, which could release water affecting heat flow. The effects of THC coupled processes that may occur due to interactions with engineered materials or their alteration products include (i) changes in water chemistry that may result from interactions between cementitious materials and groundwater, which may affect groundwater flow; (ii) dissolution of the geologic barrier by a hyperalkaline fluid that could lead to changes in the hydraulic properties of the geologic barrier; and (iii) precipitation of calcite along fracture surfaces as a result of migration of a hyperalkaline fluid that could affect hydraulic properties. Changes in pore-water and gas chemistry due to microbial processes on flow may not need to be considered in the TSPA.

### 4.3.2.1.3 Radionuclide Transport in the Unsaturated Zone

The discussions and technical basis on the RT in the UZ abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The relationship of this ISI to others is illustrated in Figure 3. The relationships between RT in the UZ and other ISIs are illustrated in Figure 10.

The model abstraction of RT through the UZ assumes the UZ could be composed of portions that act as a porous medium and other portions that act as a fractured medium. The model abstraction is based on the $K_d$ approach, where the velocity of the radionuclide relative to that of water is expressed by

$$R_f = \frac{v_w}{v_m} = 1 + \frac{\rho}{n} K_d$$

where $R_f$ is the retardation factor, $v_w$ is the average linear velocity of water, $v_{rn}$ is the average linear velocity of the radionuclide, ρ is the bulk density, n is the moisture content, and $K_d$ is the sorption coefficient.

As mentioned previously, four KTIs supply information to the RT in the UZ ISI. RT initiates in the near field. Therefore, information identified in the ENFE KTI that addresses RT in the near field will be used in this ISI. Also, the subissues that apply to this ISI from the RT KTI are RT through porous rock and RT through fractured rock. The deep percolation subissue of USFIC identifies that the distribution of groundwater flux through the UZ is needed. Finally, the network of fractures constituting groundwater flow paths in the UZ is identified in the SDS subissue dealing with fracture framework.

The processes that influence transport of dissolved radionuclides in the UZ are sorption, precipitation, dispersion, diffusion, and radioactive decay in the nonwelded units that underlie the repository. Processes that influence radionuclides associated with colloids include those processes described previously for the dissolved species along with filtration and settling.

Transport of radionuclides through the UZ can be important to performance if the estimated travel time through the UZ constitutes a significant percentage of the total travel time from the repository to the critical group. This condition depends on the physical flow system, where thick beds of porous nonwelded tuff can result in significant retardation due to the increased surface area available for sorption reactions in this type of medium. If, on the other hand, the porous beds can be bypassed as might result from lateral diversion and subsequent flow down faults, the UZ might be ineffective in isolating waste. The process of retardation does not reduce concentrations, but delays the breakthrough of the contaminant to the critical group. With the 10,000-year compliance limit proposed in 10 CFR Part 63, the delay of radionuclides to the critical group can result in site compliance when the travel time exceeds the 10,000-year period.

Important characteristics of the UZ transport model are described in the DOE TSPA-VA (U.S. Department of Energy, 1998a), which includes consideration of matrix diffusion in the UZ. Unlike the NRC TPA effort (Mohanty and McCartin, 1998), which neglects matrix diffusion in the

UZ due to a lack of convincing physical evidence of its effectiveness, the TSPA-VA includes matrix diffusion as an attenuation process.

The following are examples of possible important physical and chemical phenomena and couplings with other ISIs (see Figure 10):

- The pH and dissolved constituents may affect the sorption characteristics (radionuclide release rates and solubility limits).

- The amount of flow in fractures affects the importance of retardation in fractures (flow paths in the UZ).

Calculation of the radionuclide velocity field in the UZ involves using an equation first proposed by Vermeulen and Heister (1952) to describe the velocity of dissolved ions in a flowing system relative to the velocity of the water carrying the ions. Processes, such as ion exchange with and adsorption on solids, slow the movement of the ions. The ions spend part of the time on the immobile solid phase (e.g., sand grains) and part of the time in the moving water. This equation is valid only if the following three implicit assumptions are considered to be appropriate:

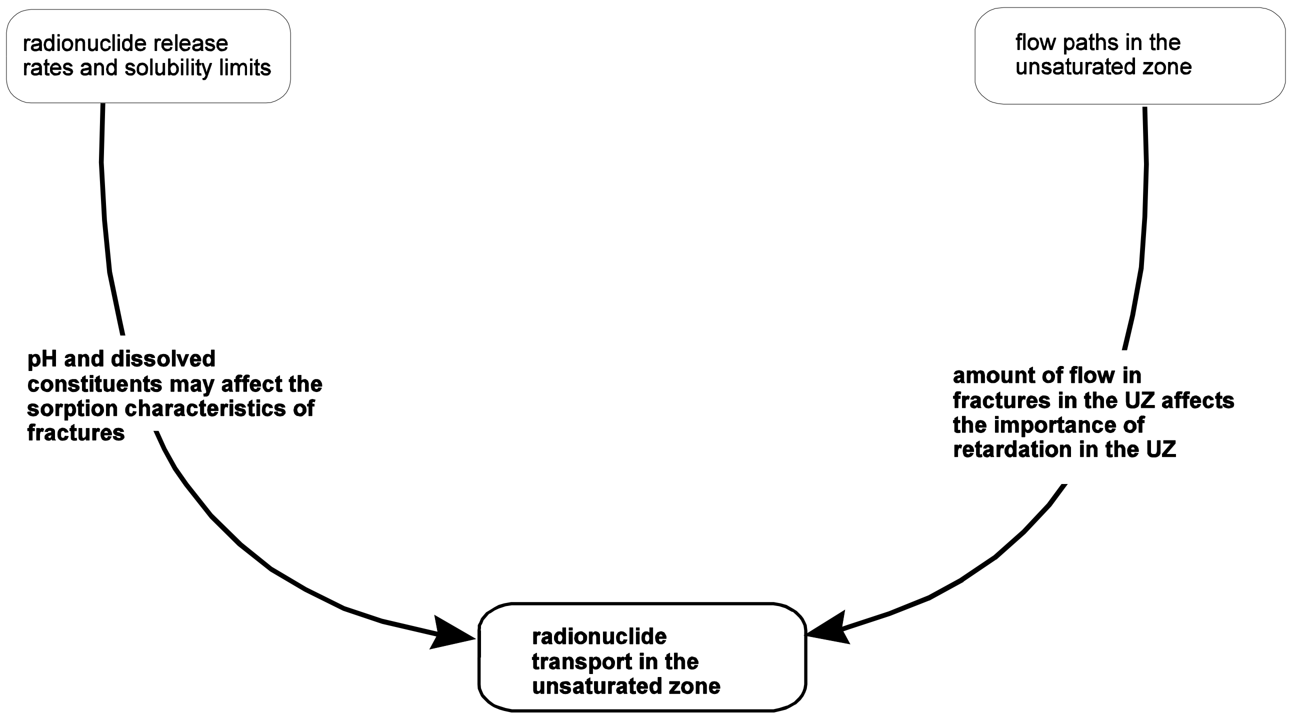
- Linear isotherm (equivalent to a constant $K_d$) (Freeze and Cherry, 1979)
- Fast reversible ion exchange and adsorption reactions (Freeze and Cherry, 1979)
- Constant bulk chemistry (Meijer, 1990)

Furthermore, this equation applies to systems in which the water is in intimate contact with the solids as in a column of granular material (e.g., crushed tuff). Such a situation allows for the maximum interaction between solute and surface sorption sites. Attempts have been made to modify this equation to apply to conditions that exist in the geologic environment and at YM. For example, in the vadose zone where the porosity is incompletely filled with water, the moisture content replaces porosity in this equation. Conca and Triay (1996) provide one example that illustrates a general agreement between the $K_d$ of selenium determined in an unsaturated flow experiment with that in a batch sorption test conducted under saturated conditions.

Bouwer (1991) provides a simple hypothetical example to show that if preferential pathways occur in porous media, the rate of solute transport can be significantly affected. In his example, when the cross-sectional area of preferential paths are 0.1 of the total cross-sectional area of the one-dimensional flow system (termed “fingering ratio”), the rate of RT was increased by a factor of 10. When the fingering ratio was 0.01, the RT was increased 100 times. From the example, he concludes, “that compounds with high $K_d$ can still be relatively mobile in the underground environment.”

There are examples at YM suggesting that preferential flow-paths exist in the UZ. Studies involving $^{36}Cl$ distribution in the ESF (Fabryka-Martin, et al., 1996) suggest isolated pathways (possibly through-going faults) from the ground surface to the repository horizon. Discrete fracture modeling (Anna, 1998) using geologic surveys of fractures within the ESF suggested that the fracture network was sparse (possibly suggesting the fingering ratio is small).

The evidence for preferential pathways at YM coupled with the example from Bouwer describing the effect of preferential pathways on RT provides the technical basis for this acceptance criterion. Currently, there are experiments (Bussod and Turin, 1999; U.S. Department of Energy, 1998a,




* Relationships in bold are identified in the text

**Figure 10. Diagram of the relationships between “radionuclide transport in the unsaturated zone” and other integrated subissues**

Volume 1, Appendix C) planned at the UZ Transport Test Facility on Busted Butte, located about 5 km south of the potential repository, designed to address the following PA needs:

- Confirm the validity of the dual permeability UZ transport process models
- Validate the laboratory databases on sorption and matrix diffusion
- Confirm the validity of the minimum $K_d$ approach at the field-scale
- Assess the role of heterogeneities such as fractures in the Calico Hills formation (e.g., fracture-matrix interaction within the Calico Hills nonwelded tuff)
- Investigate colloid mobility in fractured welded and nonwelded rocks
- Determine fracture flow and transport mechanisms in unsaturated rocks
- Investigate the effect of permeability contrasts at welded/nonwelded contacts
- Develop testing capabilities for possible future experiments beneath the repository horizon (i.e., east-west drift extension)

The DOE tests planned at Busted Butte may provide information to support the demonstration that the Calico Hills nonwelded unit acts as a porous medium. Phase 1 experiments include reactive and nonreactive tracer tests (5-month duration) in the nonfractured upper Calico Hills Formation, and in the fractured Calico Hills below the basal vitrophyre of the Topopah Springs Tuff. Phase 2 tests are longer duration (13 to 18 months) reactive and nonreactive tracer tests in a 10 × 10 × 6 m underground test block (U.S. Department of Energy, 1998a, Volume 1, Appendix C). Nonreactive tracers include potassium iodide, pyridone, and five separate polyfluorinated benzoic acids. Polystyrene latex microspheres are being injected to investigate colloid movement, and a number of reactive tracers such as nickel, molybdenum, cerium, and rhenium are being injected. Phase 1a experiments (unfractured Calico Hills) started in April 1998, and Phase 1b (fractured Calico Hills) started in May 1998. Phase 2 work has included characterization and instrumentation of the block, and Phase 2a tracer injection began in July 1998. Modeling studies predict that nonreactive tracer breakthroughs should occur within a year, while sorbing tracers should not reach the sampling locations for more than 1 year. A chromatographic separation of reactive and conservative tracers provides field-scale evidence of porous media flow and transport. Extrapolation of the properties and fracture spacing of the Calico Hills nonwelded tuff at Busted Butte to YM will require further verification.

Possible methods for demonstrating porous media flow on various spatial scales may include

- Determining the homogeneity of dye distribution on pore surfaces of an intact porous rock saturated with dye
- Demonstrating for unsaturated flow that conditions do not lead to fingering or preferential flow
- Conducting cross-hole tracer tests to characterize chromatographic separation of reactive and conservative tracers

- Performing pump tests to determine the extent of preferential paths

Some of these methods have already been used to characterize the flow medium at YM, whereas others may be included in plans for future testing.

Lacking a demonstration of porous media flow, there remains uncertainty regarding the distribution of UZ groundwater flow between fractures and matrix. Aside from issues of advective flow, this distinction is critical to consideration of retardation potential because of differences between the fractures and matrix in mineral assemblages and water chemistry (Triay, et al., 1996; Bish, et al., 1996; Murphy and Pabalan, 1994; Yang, et al., 1996, 1998) and the available surface area for adsorption. The key aspects of this ISI are

- Fracture sorption characteristics are functions of fracture mineralogy, which may differ significantly from the mineralogy of the host matrix. For example, if UZ flow is concentrated in fractures, then highly sorptive zeolite minerals may not be effective in retarding RT if they are sparse in fracture assemblages. Groundwater moving through fractures may be primarily interacting with relatively nonsorptive, comparatively low-surface-area minerals such as quartz and calcite.

- Typical application of the retardation factor in transport models assumes the sorption reactions that underlie $K_d$ are linear, reversible, and fast in comparison to the transport rate of the radionuclide within the fracture. Whether or not this assumption is valid must be resolved, in light of possibly rapid transport rates along fractures.

- Matrix diffusion is one potential component of retardation of fracture-borne solutes. For example, in the UZ, matrix diffusion could retard RT by removing solutes from fracture water and sequestering them in more sorptive matrix minerals. However, there are indications from the YM water chemistry that fracture and matrix waters may have only limited chemical interaction (Murphy and Pabalan, 1994). The question of whether or not matrix diffusion in the UZ is likely to constitute an effective retardation mechanism remains open until confirming data are available.

- Some radionuclides, particularly plutonium, may be mobile in groundwater chiefly as colloids or particulates. These modes of occurrence obviate the application of solute/solid chemical relationships such as adsorption, precipitation, and diffusion. In this case, retardation is primarily achieved by filtering. The potential for significant colloid/particulate transport of a given radionuclide should be considered when modeling retardation.

- The retardation factor assigned to a given stratum for a particular radionuclide is assumed to be constant in most models. However, changes in water chemistry or fracture mineralogy due to water-rock interaction or repository heating may result in temporal or spatial variations in $K_d$.

#### 4.3.2.2 Saturated Zone Flow and Transport

In this section, the descriptions and technical basis for acceptance criteria and review methods for the two key elements in the saturated zone flow and transport abstraction are discussed, as identified in Figure 3 (i.e., flow paths in the SZ and radionuclide transport in the SZ). The key elements for this abstraction were derived from the staff experience during previous and current performance assessment activities, reviews of DOE's TSPAs, sensitivity studies performed at the process and system level, and reviews of DOE's hypotheses in its Repository Safety Strategy. Further, these key elements represent the essential factors to be considered in demonstrating the SZs capability to improve total system performance.

#### 4.3.2.2.1 Flow Paths in the Saturated Zone

The discussions and technical basis on the flow paths in the SZ abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The flow paths in the SZ ISI addresses the groundwater flux and direction of flow, principally in the tuff and alluvial aquifers. This ISI is derived from the SZ component of the geosphere subsystem (Figure 3). The relationships between flow paths in the SZ and other ISIs are illustrated in Figure 11.

The SZ flow pathway is the most likely pathway for the transport of radionuclides from the proposed repository to the accessible biosphere at receptor locations downstream of YM. Radionuclide dose to the critical group at the receptor location is dependent on the transport times from the repository to the receptor locations, the radionuclide concentration in the groundwater at the receptor location, and dilution due to pumping from the production wells. The first two mechanisms are discussed in this ISI; the third mechanism is discussed in the dilution of radionuclides in groundwater due to well pumping ISI.

The groundwater flow system model will provide the likely direction of flow and the flow rates for RT. The flow paths in the SZ ISI addresses the groundwater flux and direction of flow, principally in the tuff and alluvial aquifers. The presence of fast pathways, due to geologic structural controls, is expected to reduce the transport time. The presence of alluvium along the groundwater flow path is expected to significantly delay the arrival of radionuclides at the receptor locations. Mixing and the resulting dilution of radionuclides in the groundwater along the flow path between the repository and the receptor location will also affect the radionuclide dose at the receptor location.

Radionuclides introduced into the groundwater below the repository horizon are mixed in SZ groundwater by pore- to fracture-scale mechanical dispersion and aquifer- to basin-scale macro-dispersion during transport. Basin-scale groundwater flow patterns in the tuff aquifer are likely to be complex and controlled by high-permeability features such as faults and zones with interconnected fractures, hence, mixing processes at the aquifer-scale may be significant. Flow-fields within the tuff aquifer may be complicated and difficult to define; however, there is abundant evidence from the test wells at YM that the flow is largely confined to highly conductive production zones within horizontally continuous layers (Geldon, 1993), except where highly fractured production zones are offset across faults. These production zones can transmit varying amounts of water depending on their thickness and extent, transmissivity, and the magnitude of the natural and imposed hydraulic gradients. Properties of the production zones, such as thickness and effective porosity, will also affect the sorption and dispersion of radionuclides during transport.

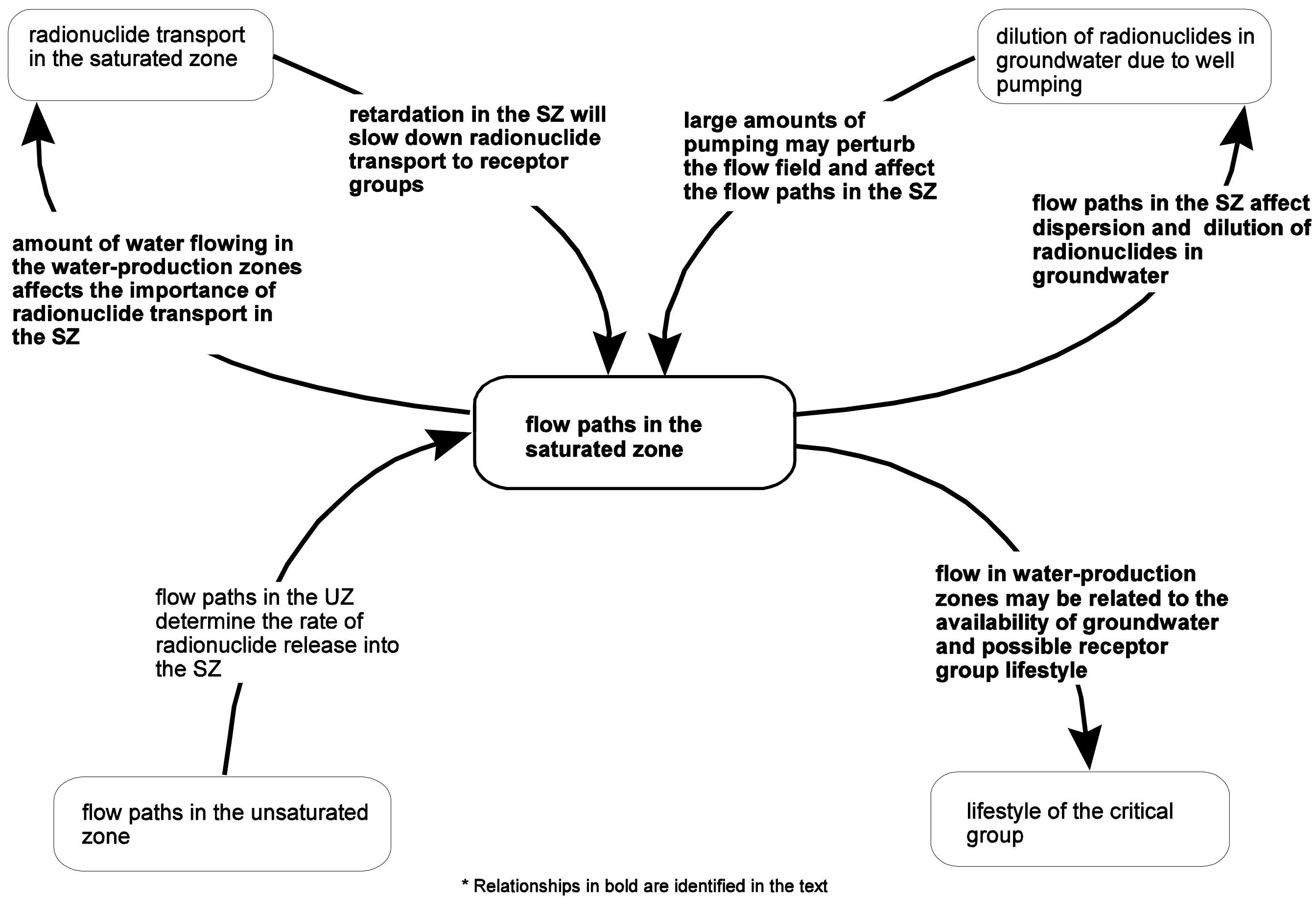



**Figure 11. Diagram of the relationships between “flow paths in the saturated zone” and other integrated subissues**

The following are examples of possible important physical phenomena and couplings with other ISIs (see Figure 11):

- Pumping rates, if large enough, may perturb the flow-field and affect flow paths in the SZ. Flow in water-production zones affects dispersion and hence dilution of radionuclides in groundwater (dilution of radionuclides in groundwater due to well pumping).

- Flow in production zones may be related to the availability of groundwater and hence possible receptor group locations and lifestyle (location and lifestyle of critical group).

The presence of alluvium along the groundwater flow path is expected to significantly delay the arrival of radionuclides at the receptor location due to enhanced sorption and dilution; however, the location of water table transition from tuffs to alluvium is not yet reasonably characterized. There is uncertainty as to where SZ flow enters the alluvium along the flow path from the repository. This is especially important considering the potential higher sorption coefficients of some radionuclides, such as neptunium, in the alluvium (U.S. Department of Energy, 1998a, Volume 3, pp. 6-24 and 6-25).

Flow paths in the SZ are affected by basin-scale groundwater flow, and may therefore be controlled by high-permeability features or channelized pathways in the aquifer. The presence of preferential or fast pathways, due to geologic structural controls, is expected to significantly reduce the transport time. In the YM vicinity, the faults locally control groundwater flow and may provide paths for upward flow from the deeper carbonate aquifer (Fridrich, et al., 1994; Bredehoeft, 1997). Such flow channeling along preferred paths is common in fractured and faulted rock (Tsang and Neretnieks, 1998). Interpretation of aquifer borehole tests indicate that permeability at YM is anisotropic (Geldon, 1996). The anisotropic permeability due to structural features downgradient of YM may result in more southerly-directed flow paths than currently modeled by the DOE. The radionuclides in this southerly flow path could remain in the volcanic tuff aquifer nearly all the way to receptor locations at 20 km, which would reduce the saturated alluvium in the flow path.

The regional- and site-scale SZ models are calibrated to match a system that is not yet reasonably characterized and only a limited amount of information is available for water table configuration, subsurface geology, and hydraulic parameters for the alluvium. The effects of natural recharge caused by infiltration along the Fortymile Wash and vertical flow from the deeper carbonate aquifer is also not reasonably addressed.

Uncertainties about SZ flow and transport at YM have been documented in two IRSRs by NRC staff (U.S. Nuclear Regulatory Commission, 1999c,h). NRC uses the collective work of all relevant parties as the technical bases for its review. TRW Environmental Safety Systems, Inc. (1998) and the DOE (1998a) suggest that the groundwater flow system in the YM vicinity has not yet been adequately characterized. There are limited field data to characterize SZ flow between about 5 and 20 km downgradient from the repository (U.S. Department of Energy, 1998a, Volume 4, p. 2-38). Limited data exist to define SZ transport along the groundwater flow pathway from the repository to the receptor location (U.S. Department of Energy, 1998a, Volume 3, p. 6-36). In addition, there are conceptual uncertainties, that have been documented by DOE and a number of other concerned parties, about modeling and representation of the SZ in the TSPA (Luckey, et al., 1996; Czarnecki, et al., 1997; D'Agnese, et al., 1997; U.S. Department of Energy, 1998a; Geomatrix Consultants, Inc., 1998; Gelhar, 1998; U.S. Nuclear Waste Technical Review Board, 1998).

A DOE peer-review panel suggested that the streamtube approach be modified to better handle dispersion and dilution (U.S. Department of Energy, 1998d). The presumed dilution, which is caused by uniform spreading and mixing of RNs at the water table and in the SZ, is nonconservative because it will overestimate the dilution when only a small number of canisters are releasing radionuclides.

#### 4.3.2.2.2 Radionuclide Transport in the Saturated Zone

The discussions and technical basis on the RT in the SZ abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

This ISI describes the transport of radionuclides in saturated subsurface environments. The relationship of this ISI to others is illustrated in Figure 3. The relationships between RT in the SZ and other ISIs are illustrated in Figure 12.

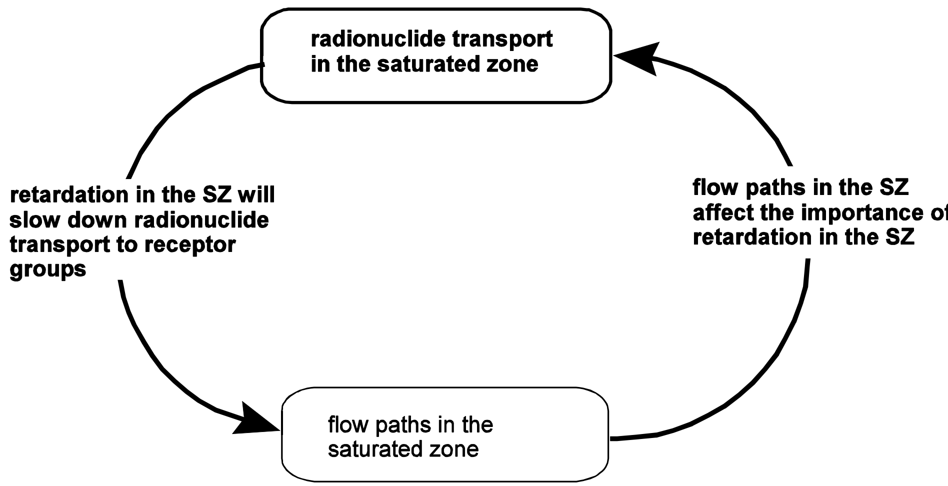
The model abstraction of RT through the SZ assumes the SZ could be composed of portions that act as a porous medium and other portions that act as a fractured medium. The model abstraction is based on the $K_d$ approach where the velocity of the radionuclide relative to that of water is expressed by

$$R_f = \frac{v_w}{v_m} = 1 + \frac{\rho}{\theta} K_d$$

where $R_f$ is the retardation factor, $v_w$ is the average linear velocity of water, $v_{rn}$ is the average linear velocity of the RN, ρ is the bulk density, ρ is the porosity, and $K_d$ is the sorption coefficient.

For the valid application of this abstraction, a number of conditions have to exist. The medium through which the groundwater flows must act as a single porous continuum. If preferential pathways exist in the medium, the use of the previous equation is invalid. Other conditions are the sorption reaction must be fast relative to the rate of groundwater flow, the isotherm must be linear, and the bulk chemistry of the system must be constant. If these conditions do not exist, other model abstractions are needed to replace the $K_d$ approach. For example, if the bulk chemistry can not be shown to be constant, process models such as surface complexation may be used in place of the $K_d$ approach. Also, if the medium through which the RN-contaminated groundwater flows is not a single continuum, the $K_d$ approach should be replaced by the model abstraction of RT through fractured rock (Holonich, 1999).

The beginning of the path the radionuclides take in the SZ starts at the water table directly below the repository. The information identified in the RT in the UZ ISI will be used as input to this ISI. Also, the subissues that apply to this ISI from the RT IRSR are RT through Porous Rock, RT through Alluvium, and RT through Fractured Rock. The SZ Ambient Flow Conditions and Dilution Processes subissue of USFIC identifies that distribution of groundwater flux through the SZ is needed. Finally, the network of fractures constituting groundwater flowpaths in the SZ is identified in the SDS Fracturing and Structural Framework of the Geologic Setting subissue. The main processes important to performance in the SZ that are considered in this ISI involve the flow system from the water table beneath the repository to the critical group. The processes that influence transport of dissolved radionuclides in the SZ are sorption, precipitation, dispersion,




* Relationships in bold are identified in the text

**Figure 12. Diagram of the relationships between “radionuclide transport in the saturated zone” and other integrated subissues**

diffusion and radioactive decay in the nonwelded units that underlie the repository. Processes that influence radionuclides associated with colloids include those processes described previously for the dissolved species, along with filtration and settling.

The transport of radionuclides through the SZ has been shown important to performance if the estimated travel time through the SZ constitutes a significant percentage of the total travel time from the repository to the critical group. This condition depends on the physical flow system, where thick beds of porous nonwelded tuff or alluvium can result in significant retardation due to the increased surface area available for sorption reactions in this type of medium. If, on the other hand, the porous beds can be bypassed as might result from preferential flow paths as along faults and fractures, the SZ might be ineffective in isolating waste. The process of retardation does not reduce concentrations but delays the breakthrough of the contaminant to the critical group. With the 10,000-year compliance limit described in 10 CFR Part 63, the delay of radionuclides to the critical group can result in site compliance when the travel time exceeds the 10,000-year period.

Important characteristics of the SZ transport model are described in the DOE TSPA-VA (U.S. Department of Energy, 1998a), which includes consideration of matrix diffusion in the UZ. Unlike the NRC TPA effort (Mohanty and McCartin, 1998), which ignores matrix diffusion in the SZ due to a lack of convincing physical evidence of its effectiveness, the DOE TSPA-VA includes matrix diffusion as an attenuation process. NRC sensitivity analyses identified SZ transport parameters as influential to overall system performance (Mohanty, et al., 1999).

The following are examples of possible important physical phenomena and couplings with other ISIs (see Figure 12):

- pH and dissolved constituents may affect the sorption characteristics (Radionuclide release rates and solubility limits).

- Amount of flow in fractures affects the importance of retardation in fractures (flow paths in the SZ).

The C-Hole tracer tests are the only field tests in the SZ that provide direct information concerning transport of reactive, nonreactive, and colloidal material. Consequently, these tests are considered crucial to establishing transport in the SZ. Reimus (1996) states, “The objective of the [C-Hole] program is to generate data for developing and testing conceptual models of flow and RT over large scales in the fractured-dominated flow in the SZ, with emphasis on studying the mechanisms of solute matrix diffusion and sorption.” Prior to performing the field tests, he made predictions concerning the breakthrough curves of the reactive, nonreactive, and colloidal tracers. For reactive tracers, he states, these “… will diffuse into the matrix and sorb to rock surfaces that they come in contact with, thus delaying their arrival and suppressing their recovery even more than the conservative solutes.”

Laboratory experiments were conducted before the C-Hole tracer tests to characterize the effects of sorption of the reactive tracer on its mobility relative to that of the nonreactive tracer. The reactive tracer both in the laboratory and the field tests was the lithium ion. The nonreactive tracer was the bromide ion. The laboratory experiments included batch sorption tests to determine the isotherm for Li, and dynamic crushed tuff column and fracture flow tests involving lithium and bromide. The batch sorption tests showed that Li is a weakly sorbing constituent whose sorption coefficient as a function of concentration generates a slightly nonlinear isotherm.

The crushed tuff column experiment illustrated that Li had a retardation factor of two, that is, it took twice as long for the Li to break through than it did for Br. The retardation of Li in the dynamic test was consistent with that calculated from Equation 1 using the $K_d$ from the batch sorption test. However, the fracture flow experiment conducted in the laboratory showed that the Li and Br break through simultaneously, but the relative concentration of the Li peak was less than that of the Br peak. Consequently, the laboratory experiments provide two extremes in breakthrough behavior depending on the flow system.

The C-Hole tracer test injected LiBr (along with other tracers) into Well C-2 and pumped Well C-3, which is 32 m away, for 8000 hours. The peak concentrations of Li and Br breakthroughs occurred simultaneously. The only difference is that the Li concentration is less than that of Br. This result is inconsistent with equation 1 and the crushed tuff column experiment, which would suggest the breakthrough curves of the reactive and nonreactive tracers would experience chromatographic separation. The breakthrough curves in the C-Hole tracer test are qualitatively consistent with the laboratory fracture test. However, the degree to which the reactive tracer concentration is attenuated is unknown because the attenuation could be a function of numerous parameters specific to the fracture pathway. These parameters could include fracture surface area, sorption site density, spatial distribution of fracture minerals, channeling, and kinetics.

The C-Hole breakthrough curves (concentration and travel time) could not be quantitatively predicted using the laboratory experiments alone, or in concert with the hydraulic pump tests in the C-Holes. Furthermore, because the proposed draft 10 CFR Part 63 is dose based, concentrations of radionuclides are important. Consequently, tracer tests like those done in the C-Holes provide valuable additional information to resolve RT issues.

As the only cross-hole tracer experiment in the SZ, the C-Hole breakthrough curves could be assumed to reflect RT through the extent of the SZ, not just the fractured tuff. This would constitute an alternative conceptual model, in line with the objective of the C-Hole program. Then both reactive and nonreactive contaminants could reach the critical group early, maybe before the 10,000-year regulatory limit. Only the concentrations of reactive radionuclides would be reduced by some unknown amount.

The performance assessment of the HLW repository is a prediction of the safety of this system whose spatial scale extends to tens of kilometers and whose temporal scale extends to tens of thousands of years. The ability to predict tracer transport on a smaller spatial and temporal scale would lend support to the claims of providing reasonable assurance in the performance assessment.

It is anticipated that for DOE to demonstrate a capability to predict breakthrough curves in the field, the following activity are required:

- Laboratory experimentation to determine parameters to be used in process modeling ($K_d$s, and diffusivities of the tracers)

- Field studies to provide mineralogic, structural (geometric), and hydraulic characterization of the fracture network

- Geostatistical analysis of multiple cross-hole tracer field tests at various locations, spatial scales, and pumping conditions on which to compare the predictions

### 4.3.2.3 Direct Release and Transport

The descriptions and technical basis for the acceptance criteria and review methods for the two integrated subissues under direct release and transport, as identified in Figure 3 (i.e., volcanic disruption of WPs and airborne transport of radionuclides) are discussed in this section. These ISIs for this abstraction were derived from the staff experience from previous and current performance assessment activities, reviews of DOE's TSPAs, sensitivity studies performed at the process and system levels, and reviews of DOE's hypotheses in its Repository Safety Strategy. Further, the integrated subissues represent the essential factors to be considered in evaluating the effect of direct release and transport on the total system performance.

#### 4.3.2.3.1 Volcanic Disruption of Waste Packages

The discussions and technical basis on the volcanic disruption of waste packages abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The volcanic disruption of WPs ISI describes the interaction of magma with waste packages. This ISI is derived from the direct release and transport component of the geosphere subsystem (Figure 3). The relationships between volcanic disruption of WPs and other ISIs are illustrated in Figure 13.

Previous studies have shown that the annual probability of a volcanic event penetrating the repository is large enough to be considered in TSPAs (Connor and Hill, 1995; Crowe, et al., 1995; U.S. Nuclear Regulatory Commission, 1999i). A volcanic event is defined herein as the formation of a new volcano, that has a subsurface conduit that penetrates the proposed repository emplacement drifts after closure. A future volcanic eruption at the proposed YM repository site most likely would involve dense, basaltic magma at high temperatures impacting WPs for days to weeks, initially at high velocities (U.S. Nuclear Regulatory Commission, 1999i). These adverse thermal, chemical, and mechanical effects of volcanic activity likely would result in the disruption of WP containment.

The state of rock stress around the repository drifts will affect how ascending magma interacts with the drifts. Rock stress is controlled by the distribution of regional tectonic stress and likely thermomechanical effects associated with HLW emplacement. Ascending basaltic magmas have fluid overpressures on the order of 1–10 MPa above lithostatic pressure at repository depths. Local variations in the amount of force necessary to dilate existing fractures, or propagate new fracture pathways, will strongly affect the flow path of ascending magma. If magma enters the repository drift, the number of WPs impacted will depend on the repository design. The presence of backfill, drip shields, and canister spacing all will influence how far magma can flow through repository drifts.

Volcanic eruptions that potentially can occur at YM are likely to develop volcanic ash columns that reach elevations of 4–10 km above YM and are advected by wind. Therefore, volcanic disruption of the WP is important to total system performance because HLW can be transported directly to the critical group location in a single event. The resulting deposits also could potentially remain at the surface for many thousands of years. Staff analyses show that the expected annual dose from

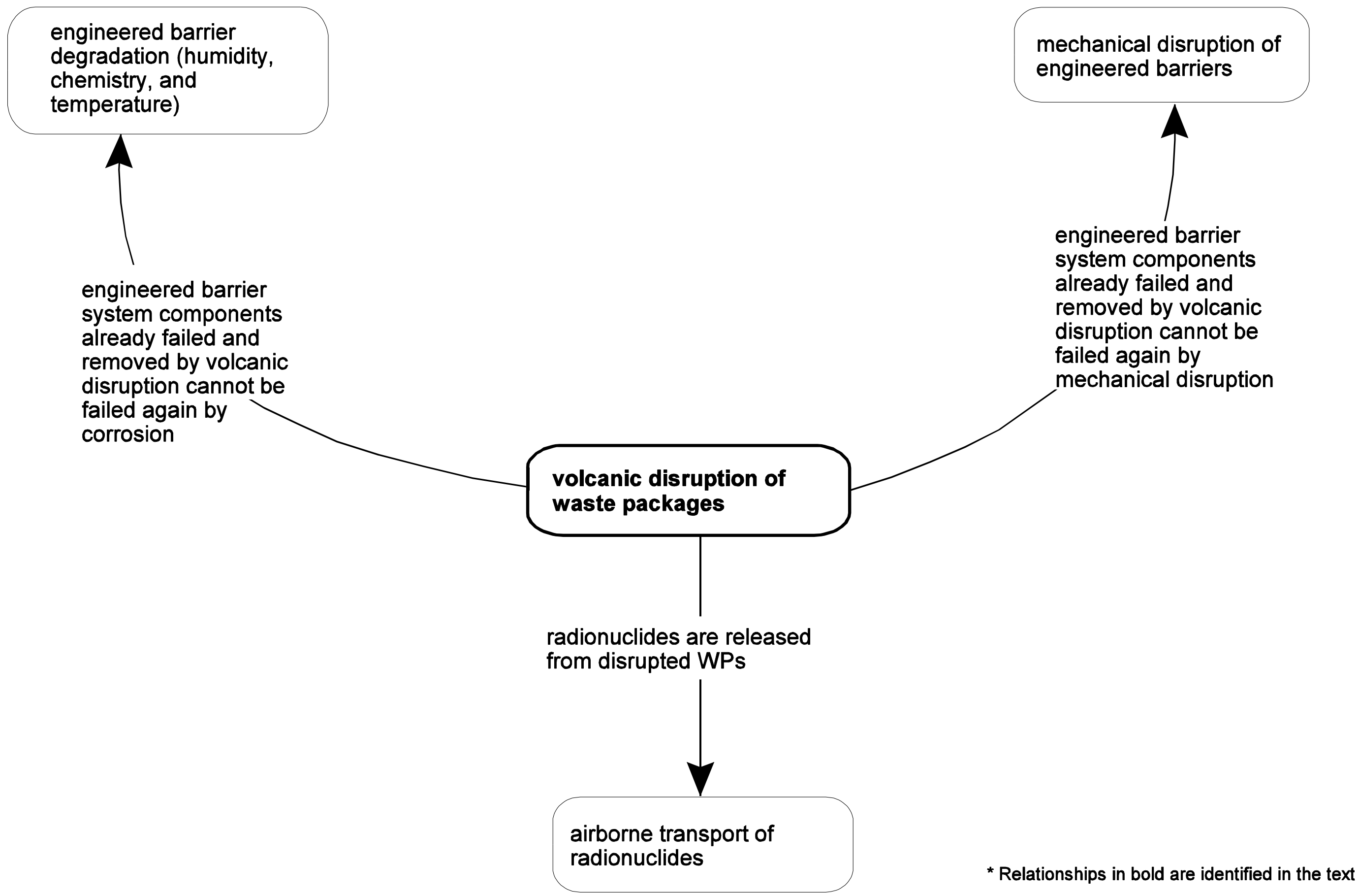



**Figure 13. Diagram of the relationships between “volcanic disruption of waste packages” and other integrated subissues**

volcanic disruption, while below the proposed performance standard in 10 CFR Part 63, currently exceeds the expected annual dose from undisturbed performance during the first 10,000 years of repository closure. These calculations and detailed discussions of the underlying technical bases are in the IA IRSR (U.S. Nuclear Regulatory Commission, 1999i).

Many of the parameters necessary for calculating the dose consequences of volcanic disruptions of the proposed repository can be bounded through modeling and observations at historical volcanic eruptions. Several features of YMR volcanoes at Lathrop Wells and Little Black Peak indicate a violent strombolian eruption style (U.S. Nuclear Regulatory Commission, 1999i), which represents an ability to fragment and transport volcanic particles for at least tens of kilometers down wind. Because recent (≤1 million years) eruptions in the YMR have preserved characteristics of violent strombolian activity, models of volcanic eruption through the proposed repository need to encompass this style of volcanism. Current TPA calculations assume the subsurface volcanic conduit has a diameter of 1–50 m, which is based on data from analog volcanoes. The number of WPs intersected by the volcanic conduit represents the HLW source term for subsequent risk calculations. Ascending magma that intersects a repository drift, however, encounters variations in lithostatic confining pressure that have not occurred at analog volcanoes. NRC currently is conducting numerical and analog laboratory experimental modeling to evaluate how ascending magma may flow after intersecting a repository drift; these effects may affect the number of WP entrained during a repository-penetrating volcanic eruption (U.S. Nuclear Regulatory Commission, 1999i).

Other parameters necessary for volcanism risk calculations, primarily related to interactions between basaltic magma and EBSs, are difficult to determine. The physical, thermal, and chemical loads imparted on a WP entrained in a volcanic conduit exceed current WP design bases. Although data and models have not evaluated WP behavior under appropriate volcanic conditions (e.g., U.S. Department of Energy, 1998a), staff conclude that WP failure during direct entrainment into a volcanic conduit is a conservative assumption (U.S. Nuclear Regulatory Commission, 1999i). Available data and models also have not evaluated HLW behavior under appropriate volcanic conditions (e.g., U.S. Department of Energy, 1998a). The physical, thermal, and chemical loads imparted on HLW particles entrained in a volcanic conduit could possibly induce fragmentation, reducing HLW average particle sizes significantly (U.S. Nuclear Regulatory Commission, 1999i).

#### 4.3.2.3.2 Airborne Transport of Radionuclides

The discussions and technical basis on the airborne transport of radionuclides abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC’s technical basis for the staff review consistent with the current design and knowledge of site conditions.

Review of the airborne transport of radionuclides model abstraction involves the IA KTI. The airborne transport of radionuclides ISI evaluates the transport of radionuclides in volcanic eruption columns and subsequent advection and dispersion of the contaminated tephra cloud in the atmosphere. Input into this model abstraction depends on the amount of radionuclides released from volcanic disruption of WPs. Output from this model abstraction is a probabilistic assessment of the mass of radionuclides deposited on the ground surface as a result of volcanic eruptions. This result is used by related subissues (lifestyle of the critical group and redistribution of radionuclides in soil) to evaluate risk (Figure 14). This ISI is derived from the direct release and transport component of the geosphere subsystem (Figure 3).

Volcanism is the only direct release mechanism currently under consideration by the NRC. This discussion focuses on the airborne transport of radionuclides that have been incorporated into volcanic tephra. Modeling the entrainment of HLW and airborne transport of tephra is a necessary step in analyzing the consequences of volcanic events. Basaltic eruptions through the repository may result in the airborne transport of HLW, contained within tephra, from the proposed repository location to receptor locations (Sagar, 1997) as illustrated in Figure 15. The latest DOE TSPA (U.S. Department of Energy, 1998a) models the direct release of RNs from a volcanic event as a disruptive event at the repository. HLW is modeled as incorporated into the ash and transported through the air to the critical group location. Specifically, this ISI relates to model abstractions for evaluating the transport and deposition of HLW incorporated within tephra.

Basaltic eruptions that build cinder cones yield dramatic variations in energy, duration, and style. Numerical models that quantify the physics of these eruptions have reached a stage of development that allows exploration of the parameters governing these variations. Thus, many of the nuances of observed eruption columns and their resulting deposits can now be understood by fundamental physical processes (e.g., Sparks, et al., 1997). Such an understanding is critical for volcanic risk assessment related to the proposed repository because there are no observations of the behavior of dense grains (i.e., HLW particles) in eruption columns. Basaltic tephra dispersion models provide an opportunity to extend our understanding of tephra plumes to encompass the distribution and deposition of dense HLW particles in tephra blankets. In these circumstances, application of physically accurate models are a fundamental step in stochastic modeling of dose and risk to the critical group. HLW is modeled as incorporated into the ash and transported through the air to the critical group location. Specifically, this ISI relates to model abstractions for evaluating the transport and deposition of HLW incorporated within tephra.

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Input to this ISI is totally contained within the IA KTI. Input from other KTIs is only indirect because they may affect volcanic disruption of the WP.

Current estimates of the probability of volcanic eruptions through the repository range from $1 \times 10^{-8}$ to $1 \times 10^{-6}$ per year (Ho, 1991; Geomatrix Consultants, Inc., 1996; Connor and Hill, 1995; Connor, et al., 2000), with NRC IA staff currently adopting a value of $1 \times 10^{-7}$ per year (U.S. Nuclear Regulatory Commission, 1999i) as a conservative bound on the probability of a volcanic eruption through the repository. Dose calculations for basaltic volcanic activity depend on numerous parameters including eruption magnitude, duration, and number of WPs disrupted by basalt magma. Current annual dose calculations do not include the potential effects of remobilization of tephra deposits located closer to YM and subsequently deposited at the critical group location.

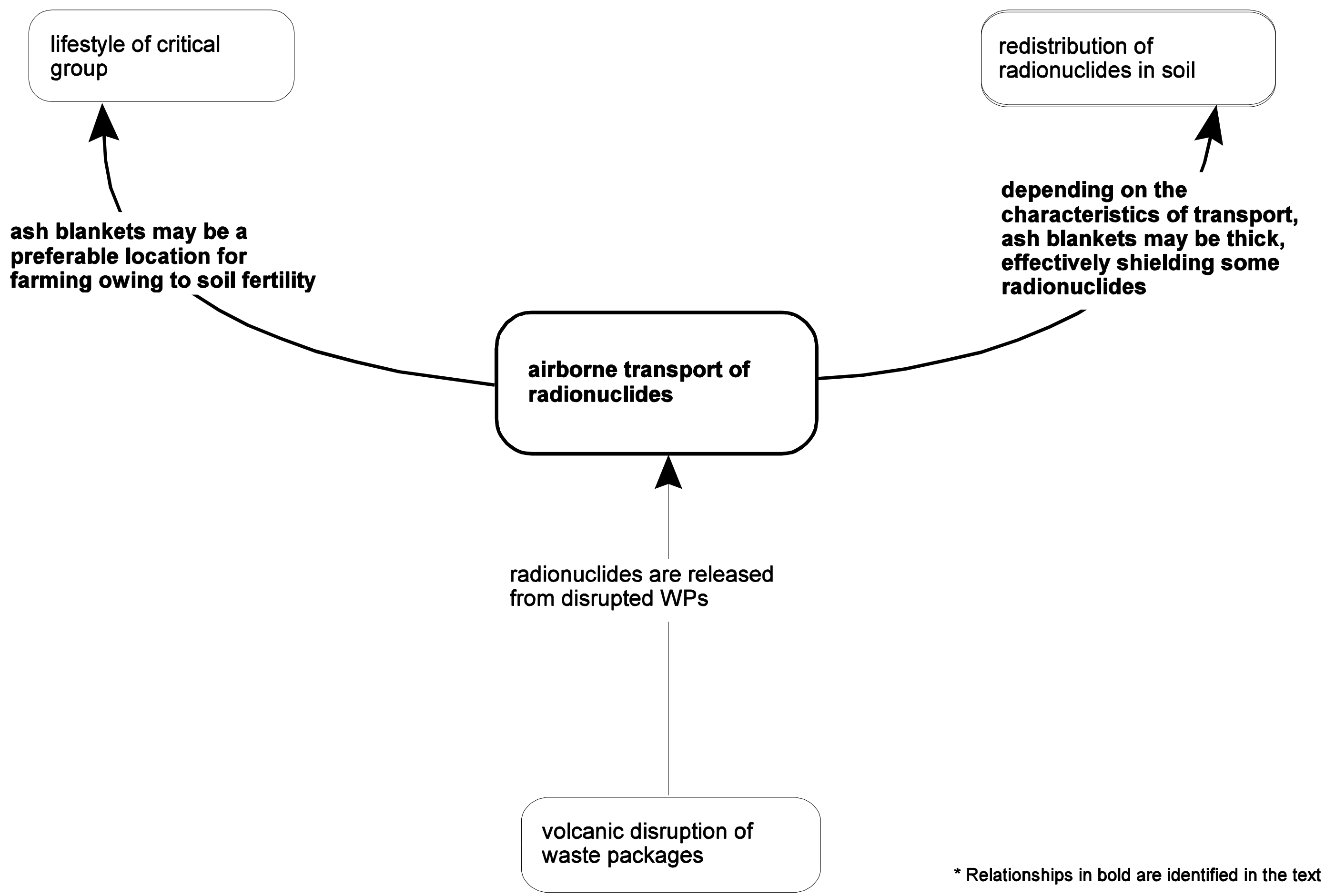



**Figure 14. Diagram of the relationships between "airborne transport of radionuclides" and other integrated subissues**

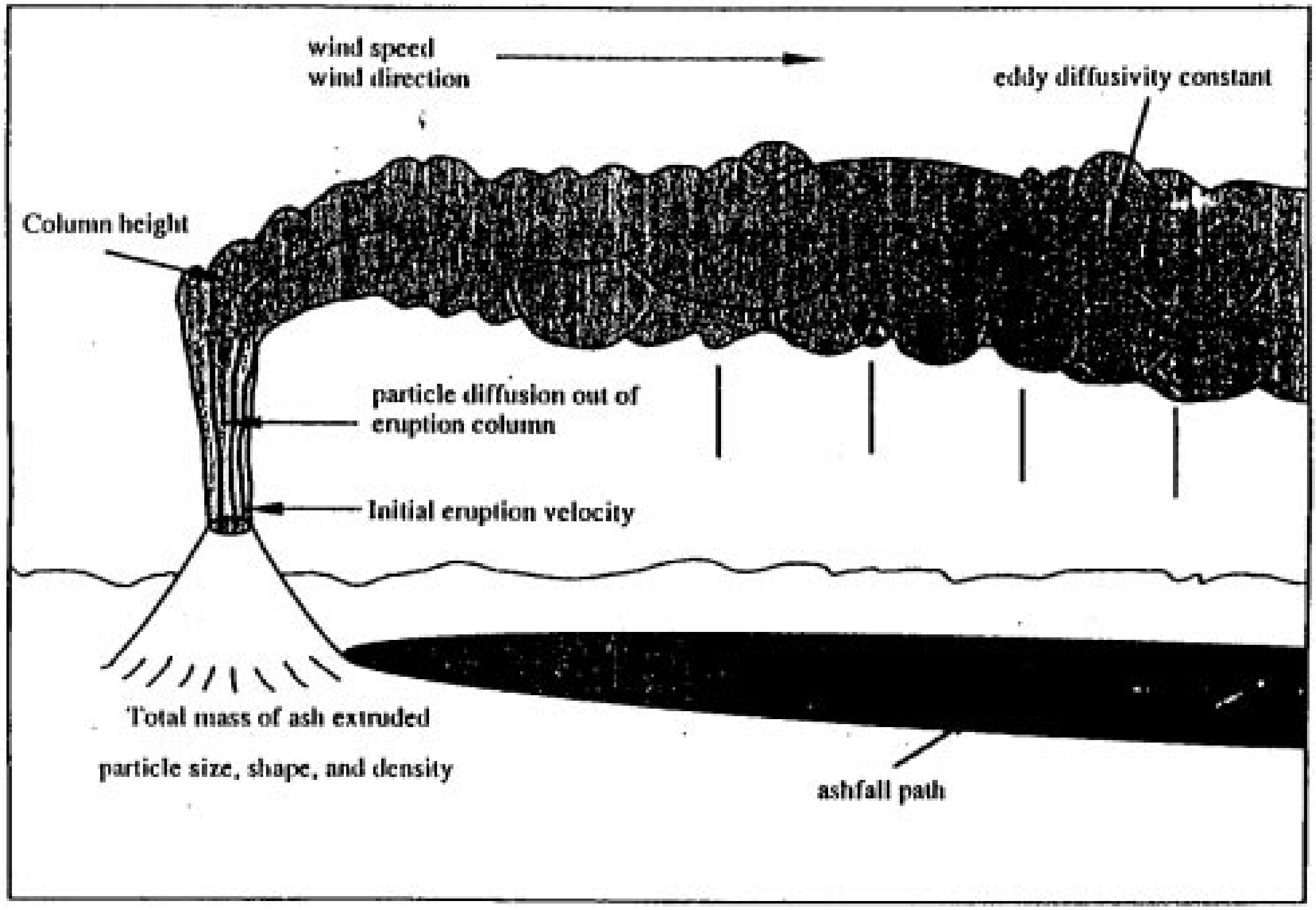



**Figure 15. Illustration of the important processes and parameters for estimating airborne transport of tephra**

Basaltic volcanoes are capable of ejecting material that can be transported tens of kilometers away by air dispersion, depending on characteristics associated with the tephra mass being extruded (e.g., size distribution, density, and others) and characteristics of the volcanic event (e.g., column height, wind speed, and others) (Jarzemba, 1997; Suzuki, 1983; Sparks, 1986; Woods, 1988, 1995). Dose calculations presented in NRC (1999i) build on previous calculations used to evaluate the possible impacts on repository performance associated with basaltic volcanism (Jarzemba and LaPlante, 1996; Jarzemba, et al., 1997). Volcanic plume models were tested against actual basaltic eruptions and other numerical models of volcanic plumes in Hill, et al. (1998). To account for uncertainties in model predictions, previous studies have sampled the values of parameters important for predicting the transport and subsequent deposition of tephra from representative probability distributions (Jarzemba and LaPlante, 1996; Jarzemba, 1997). Current NRC/CNWRA assessments address this ISI by using a model similar to a Gaussian plume model, except the volcanic column is modeled as a line source rather than a point source with material diffusing from the column at heights along the column (Jarzemba, 1997). Current NRC/CNWRA assessments conservatively assume that the wind is blowing in the direction of the critical group for the duration of the eruption.

The following are examples of important physical phenomena and couplings with other ISIs (see Figure 14):

- Depending on the characteristics of transport, tephra deposits may be thick, effectively shielding some radionuclides (redistribution of radionuclides in soil due to surface processes).

- Tephra deposits may be a preferable location for farming owing to soil fertility, (e.g., high nitrate content and root penetrability) (lifestyle of critical group).

Accurate estimates of individual dose and risk associated with volcanic eruptions through the YM repository depend on numerical models of the transport of HLW upward in a volcanic tephra column, advection and dispersion of this waste with volcanic tephra in the atmosphere, and deposition of waste in the tephra blanket at the critical group location. The accuracy of these estimates depends on capturing fundamental details of volcanic tephra plume dynamics (e.g., Sparks, 1986; Sparks, et al., 1997) of which there are limited historical examples from basaltic cinder cone eruptions. However, there are no historical examples for the behavior of waste in these columns. Models of volcanic tephra eruptions range from empirical models that can capture the general pattern of tephra dispersion without attempting to accurately portray the physics of volcanic columns (e.g., Suzuki, 1983), to thermo-fluid-dynamic models of tephra columns and tephra advection and dispersion (e.g., Woods and Bursik, 1991; Sparks, et al., 1992, 1997; Woods, 1993, 1995). These latter models make a convincing case that accurate, quantitative descriptions of tephra deposition at the ground surface result from application of physically accurate models. Thus, although computationally complex, these models can likely provide insight into the behavior of HLW in the tephra column, despite the very different physical properties of HLW compared to basaltic tephra. These same arguments for physical detail extend to the sedimentation of tephra and HLW out of the atmosphere. For example, Bonadonna, et al. (1998) have shown that a particle Reynolds number plays a critical role in particle settling velocity and, as a result, particle-size density distributions in the tephra blanket.

Although it is completely appropriate to use the simplified models developed by Suzuki (1983) in performance assessment and volcanic hazard analyses, it is crucial to delineate a physical basis for the parameter distributions used in the model. This is particularly important because the

ASHPLUME model is essentially empirical, yet the dispersal of HLW in volcanic eruptions has never been observed.

The Suzuki (1983) model does not attempt to quantify the thermo-fluid-dynamics of volcanic eruptions. The more recent class of models, pioneered by Woods (1988), concentrates on the bulk thermophysical properties of the column. A gas-thrust region is defined near the vent and a convective region above, within which the thermal contrast between the atmosphere and the rising column results in the entrainment of air. Buoyancy forces act to loft tephra particles upward. In contrast to Suzuki (1983), this class of models results in a highly nonlinear velocity profile within the ascending column. This difference can have a profound effect on the height of ascent of HLW grains in an ascending tephra column and their resulting dispersion in the accessible environment.

The current modeling approach used in ASHPLUME may underestimate the amount of HLW dispersed during some eruptions. An important conclusion from initial analyses (U.S. Nuclear Regulatory Commission, 1999i) is that velocities in the column remain high until nearly the top of the tephra column. Some particle transport in the tephra column depends on the bulk properties of the column, there is little opportunity for dense HLW grains to fall out of the erupting column unless they are advected to the column edge during ascent. This result is different than that of Suzuki (1983), who estimates the height at which material diffuses out of the column as a function of particle settling velocity. Hence, the Suzuki (1983) model predicts that dense HLW particles will tend to be “released” from the tephra column at comparatively low altitudes, resulting in comparatively lower dispersion. In contrast, the thermo-fluid-dynamic model tends to transport waste and waste-laden tephra to higher altitudes, resulting in wider dispersion of this material. The difference between these models will become more pronounced at greater eruption energies. Since these eruptions can provide the most dose to the critical group, risk analyses may be affected by these differences.

Wind velocity is another parameter that significantly affects tephra dispersion from basaltic volcanoes. The column from the next YMR eruption will likely reach altitudes of 2–6 km above ground level, which is observed for most violent-strombolian basaltic eruptions (U.S. Nuclear Regulatory Commission, 1999i). Although near-ground-surface wind data are available for the proposed repository site, low-altitude winds will be affected significantly by surface topographic effects and thus have little relevance to modeling dispersal from 2–6-km-high eruption columns (e.g., U.S. Department of Energy, 1997b). The nearest available high-altitude wind data are from the Desert Rock airstrip, located approximately 50 km southeast of YM. Based on DOE (1997b) data, average wind speeds at about 2 km above ground level (i.e., 700 mbar) are 6 m $s^{-1}$. These average wind speeds increase to about 12 m $s^{-1}$ at altitudes of about 4 km above ground level (i.e., 500 mbar). Staff conclude that an average wind speed of 12 m $s^{-1}$ provides a reasonably conservative basis to model aerial tephra dispersal from the proposed repository site. Alternatively, models that incorporate stratified variations in wind speed and direction could be used (e.g., Glaze and Self, 1991).

### 4.3.3 Biosphere

Assuming the radionuclides released from the proposed repository at YM reach the critical group location, the lifestyle of the critical group and the various physical processes occurring in the biosphere directly influence the annual exposure to the critical group. To evaluate the contribution made by the various processes in the biosphere to attain the system performance objective, current thinking is to focus on the intermediate calculations that provide distribution of radionuclide concentration, as a function of time, in soil or groundwater, used by the critical group.

#### 4.3.3.1 Dose Calculation

In this section, the descriptions and technical bases for the acceptance criteria and review methods for the three ISIs in dose calculation, as identified in Figure 3 (i.e., dilution of RNs in groundwater due to well pumping, redistribution of radionuclides in soil due to surface processes, and lifestyle of critical group), are discussed. The ISIs for this abstraction were derived from the staff experience from previous and current performance assessment activities, reviews of DOE's TSPAs, sensitivity studies performed at the process and system level, and reviews of DOE's hypotheses in its Repository Safety Strategy. Further, the key elements represent essential factors to be considered in dose calculation, which is expected to be the measure of total system performance.

##### 4.3.3.1.1 Dilution of Radionuclides Due to Well Pumping

The discussions and technical basis on the dilution of radionuclides due to well pumping abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The dilution of radionuclides due to well pumping ISI examines the methods that can be used to calculate the effects of well pumping on radionuclide concentration at the wellhead. This ISI is an important element of the dose calculation component of the biosphere subsystem (Figure 3). The relationships between dilution of radionuclides due to well pumping and other ISIs are illustrated in Figure 16.

Radionuclide dilution due to well pumping refers to mixing contaminated groundwater from a contaminant plume with uncontaminated groundwater outside the plume. Dilution due to pumping is important to the performance assessment of Yucca Mountain because it provides a mechanism by which radionuclide concentrations reaching the biosphere may be significantly reduced relative to *in situ* concentrations. This is particularly important when the extracted volume is drawn from regions beyond the contaminated zone where mixing of contaminated water with contaminant free waters occurs. For low extraction volumes, this mechanism may be of negligible importance.

The potential of dilution due to well pumping as a mechanism to reduce radionuclide concentrations reaching the biosphere has been noted by DOE TSPA-VA (U.S. Department of Energy, 1998a, Volume 3, Section 6.5.1.10, Dilution for Pumping). The NRC and CNWRA have also noted the potential importance of dilution due to pumping and have included this mechanism in the performance assessment code, TPA Version 3.2. In the NRC document, System-Level Repository Sensitivity Analyses Using TPA Version 3.2 Code, dilution due to well pumping was found to rank among the top 10 parameters most influencing repository performance after both 10,000 and 50,000 years.

The potential importance of dilution due to well pumping for lowering radionuclide concentrations reaching the biosphere and its ultimate impact on performance assessment has been discussed by Fedors and Wittmeyer (1998). The general findings of this work, which examined methods for estimating well bore dilution factors, demonstrated that significant reductions in radionuclide concentrations were possible. Research by staff at Sandia National Laboratories (CRWMS M&O, 1997) also indicated the potential for well pumping to cause significant reductions in radionuclide concentrations reaching the biosphere. This ISI is influenced by FEPs pertaining to the SZ Ambient Flow Conditions and Dilution Processes (USFIC-5) KTI subissue. Production wells for the critical group will be completed in the SZ, which constitutes a source of both contaminated and uncontaminated water. But in addition, this ISI is also strongly influenced by some of the FEPs pertaining to the lifestyle of the critical group ISI.

Review of the dilution of radionuclides due to well pumping ISI involves evaluating the approach and method(s) used to calculate the dilution effects of well pumping on the radionuclide concentrations at the wellhead. The review will include evaluating FEPs that may directly or indirectly impact the radionuclide dilution at the wellhead. This includes FEPs pertaining to groundwater flow and transport characteristics in the SZ, as well as FEPs pertaining to groundwater demand and uses at the receptor location by members of the critical group. More specifically, the abstraction of radionuclide dilution in the pumping well at the receptor location depends on factors pertaining to:

- The aquifer (e.g., aquifer yield, thickness, distribution, hydraulic properties, or water quality)
- The production well (e.g., well location, design, discharge rate, or aquifer penetration)
- The plume geometry and radionuclide concentration in the plume
- The water demand and use profile of the groundwater users at the receptor location (e.g., residential community, and farming community)

The method used to calculate radionuclide concentrations at the pumping well supplying water at the receptor location largely depends on the approach used to model the transport of radionuclides from the repository to the receptor location. If the RT model does not explicitly estimate resident concentrations, as is the case for the transport module in the NRC's TPA Version 3.2 code, the RN concentration at the well or the well field may be calculated by dividing the mass or activity of the radionuclides captured by the well(s) by the volumetric discharge rate.

If a complex three-dimensional (3D) transport model incorporating the effects of the pumping well on the flow-field is used to estimate resident radionuclide concentrations, borehole radionuclide concentrations may be explicitly calculated by flux-weighting the resident radionuclide concentrations at a cylindrical surface, centered on the borehole that corresponds to the well screen. Alternatively, if a simple, 1D streamtube model is used to simulate transport and *in situ* radionuclide concentrations are obtained, a borehole dilution factor can be used to account for the relative volumes of contaminated and uncontaminated water captured by the borehole. The term dilution factor has been used also in complex 3D transport models to express the ratio of the maximum concentration at the well bore to the average concentration caused by mixing in the well bore. In both approaches, the magnitudes of dilution factors are highly dependent on the pumping rate, receptor location, plume geometry, and aquifer characteristics. Generally, specification of the radionuclide concentration at the well head should represent the mean concentration expected at the receptor location rather than the concentration for a specific well location and, hence, precisely determined plume geometry.

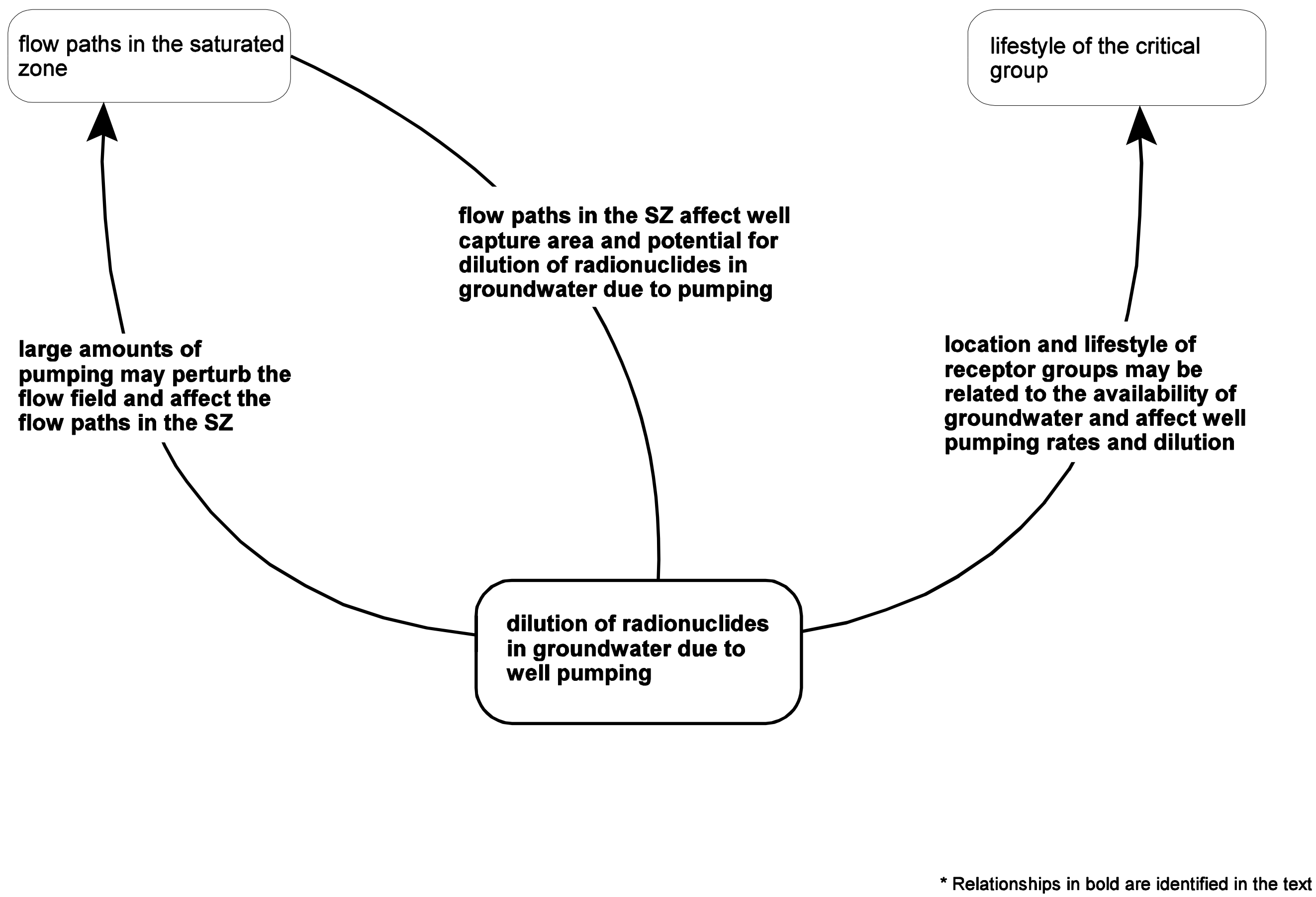



**Figure 16. Diagram of the relationships between "dilution of radionuclides in groundwater due to well pumping" and other integrated subissues**

The following are examples of important physical phenomena and couplings with other ISIs (see Figure 16):

- High pumping rates may perturb the flow-field and affect the flow paths in the SZ. Flow in water-production zones affects well capture area and potential for dilution of radionuclides due to pumping (flow paths in the SZ).

- The lifestyle of receptor groups may be related to the availability of groundwater, hence affecting well pumping rates and dilution (lifestyle of critical group).

Radionuclides dissolved in SZ groundwater may be intercepted by pumping wells downgradient from YM. Active pumping of groundwater will create cones of depression that will intercept dissolved radionuclides within its radius of capture. Local groundwater flow in the capture zone will be directed toward the well at a higher velocity than the ambient regional flow. This increased velocity, and thereby increased volumetric flow, will provide an active mixing zone for radionuclides within the capture zone that may homogenize the radionuclide concentrations. The flow into the well intake screen will be affected by the amount and distribution of pumping, the well diameter, the length of the screened interval(s), the degree of aquifer penetration by the well, and the radius of influence of the well.

Cones of depressions induced by pumping wells downgradient from YM can disrupt the ambient hydraulic gradient. Depending on their size and locations, these cones of depression may capture some or all of the radionuclides migrating downgradient from the proposed repository. Depending on the relative volumes of contaminated and uncontaminated waters drawn into the cone of depression, significant reductions in radionuclide concentrations may result, thus reducing radionuclide concentrations reaching the biosphere. Hence, in a qualitative sense, this mixing or dilution can have a significant impact on repository performance. The amount of dilution is impacted by the well location relative to the contaminant plume, aquifer properties and their degree of spatial heterogeneity, the resulting plume geometry, and, finally, well design and pumping rates. Because of the range of parameters that may impact dilution caused by pumping and its potential impact on repository performance, a review of this ISI is required.

Radionuclide dilution caused by pumping depends on the relative geometries of the well capture zone and the plume of dissolved radionuclides. If the capture zone is sufficiently large to capture the entire plume of dissolved radionuclides, the borehole concentration is computed by integrating the spatial distribution of radionuclide concentrations to obtain the total radionuclide mass or activity crossing the plane of capture per unit time. The result is then divided by the volumetric discharge rate of the well. If the capture zone is smaller than the area of the plume normal to the streamlines defining the lateral and vertical extent of the capture zone, the same calculation procedure can be used, but additional data are needed to perform the integration of the radionuclide concentrations.

Dilution caused by pumping wells ultimately depends on the pumping rates. Pumping rates, in turn, depend on the hydraulic properties of the aquifer, the hydraulic properties of the well at the receptor location, the geometry of the contaminant plume, and the plumes proximity to the receptor location. The performance assessment may have to involve analyses of all of these factors based on available information pertaining to the site and the presumed location and lifestyle of members of the critical group.

#### 4.3.3.1.2 Redistribution of Radionuclides in Soil

The discussions and technical basis on the redistribution of radionuclides in soil abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The redistribution of radionuclides in soil ISI addresses the processes that cause concentration or dilution of radionuclides in the soil after deposition by a volcanic event or irrigation with contaminated water. This ISI is derived from the dose calculation component of the biosphere subsystem (Figure 3). The relationships between redistribution of radionuclides in soil and other ISIs are illustrated in Figure 17.

This ISI relates to the calculation of the redistribution of radionuclides in the soil due to deposition of a volcanic ash blanket or application of contaminated water on the soil. Irrigation with contaminated water or deposition of contaminated ash will create a layer of contamination on the surface soil. Humans can be exposed through many pathways from contaminated soil (e.g., external, incorporation in foodstuffs, inhalation of resuspended materials). In general, the computational models use the concentration of radionuclides per either unit volume or mass. While the initial deposition could create a concentrated layer of contamination, both human and natural processes can lead to dilution. Plowing of the soil will mix the contamination throughout the plow zone, and leaching of radionuclides could make them unavailable for uptake through surface exposure pathways. Leaching of the contaminated surface, both in the area of the critical group and throughout the drainage basin (in the case of an ash blanket), into the groundwater system could increase groundwater concentrations and therefore, increase doses from groundwater use. Areas that are not subject to tilling, such as yards, would not be subject to mechanical dilution, but would still be subject to processes such as weathering, leaching, and radioactive decay.

The consequences of an extrusive volcanic event will be the incorporation of SNF in ash particles and subsequent release from the repository to the accessible environment. The radionuclides released will be transported through the air by the ash plume and deposited on the ground surface in an ash blanket. Because the Fortymile Wash deposits sediments in an alluvial fan near the location of the critical group, the transport of the ash blanket in the upstream portions of Fortymile Wash and redeposition of contaminated ash and other soils in the region of the critical group could be a route that replenishes contamination levels.

For the nominal case (barring disruptive events such as extrusive volcanism), it is assumed that contaminants will travel through the local aquifer system (see RT3) into the region of the critical group. The critical group could use the contaminated groundwater for irrigation, watering animals and yards, and various domestic activities, including use as drinking water. The use of the contaminated water on crop fields or yards will form a contaminated layer of soil. The watering of a certain area of land could continue over a long time frame. The contaminants would be replenished all the time as processes such as crop uptake, radioactive decay, and leaching reduced contaminant levels in the surface soil. Over time, the contaminant level in the soil could increase if the application rate was higher than the total of the various loss rates, which could result in higher doses through the external, inhalation, and ingestion pathways.

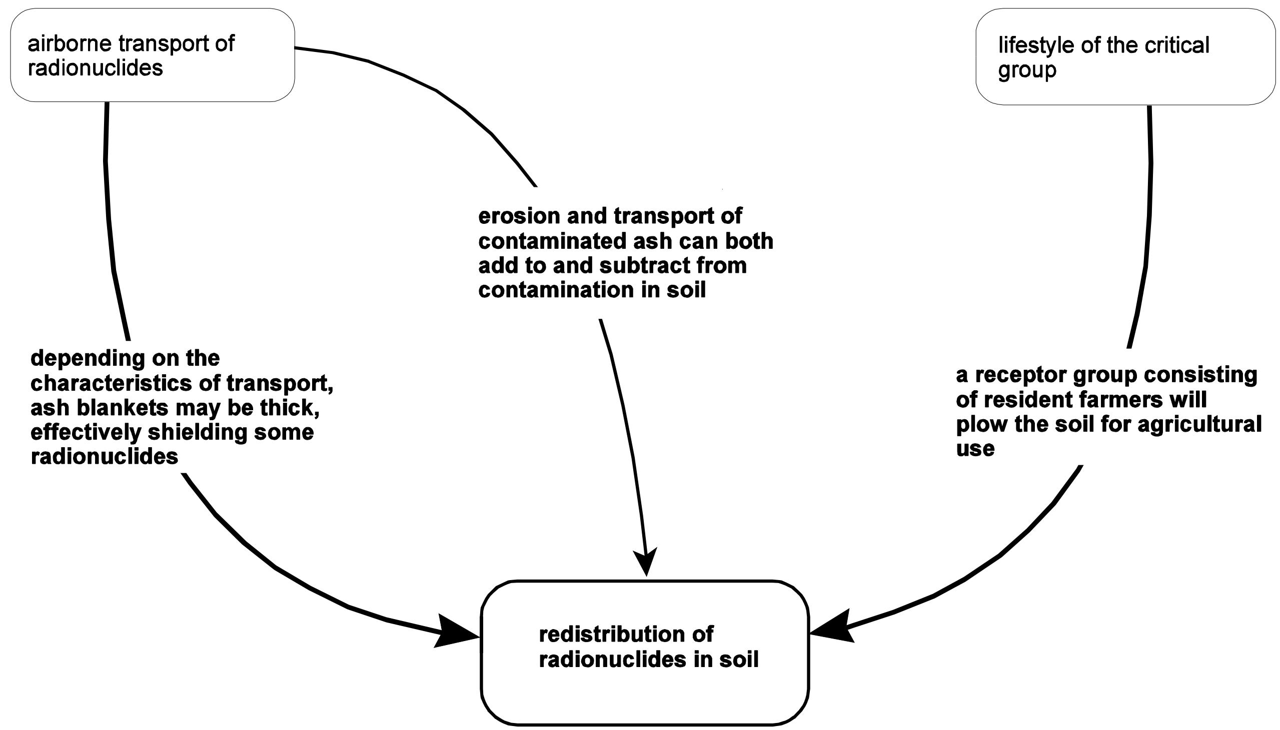
The following are examples of important physical phenomena and couplings with other ISIs (see Figure 17):

- A receptor group consisting of resident farmers will plow the soil for agricultural use (lifestyle of critical group).

- Depending on the characteristics of transport, ash blankets may be thick, effectively shielding some radionuclides (airborne transport of radionuclides).

- Leaching of the ash blanket and downward transport to the groundwater system could increase the dose from the groundwater pathway (radionuclide transport in the UZ).

As a result of processes affecting the biosphere (e.g., growth of plants for animal and human consumption only in surface soil layers, resuspension of contamination solely from soil surface layers, and others) and physical properties of radiation (e.g., limited ability to travel through matter without interaction), only radionuclides that exist fairly close to the surface are capable of exposing members of a receptor population to radiation. The depth beyond which radionuclides cannot contribute to doses to receptor populations differs, depending on the process and the assumptions regarding the root depth. For example, some plant types, such as carrots, are able to extract soil water from only the top 15 cm or so of soil, however, alfalfa has a tap root that can penetrate several meters into the soil (LaPlante and Poor, 1997). Another example of how the dilution of radionuclides in soil affects dose rates to exposed populations is the relatively lower contribution to direct exposure dose rates above the soil due to contamination in deeper soil layers. This phenomenon is known as self shielding. Consider a situation in which a soil is uniformly contaminated with $^{60}Co$, a gamma-emitting nuclide whose decay emits gamma rays at 1.17 and 1.33 MeV. These gamma rays are relatively high in energy compared to gamma rays emitted from other radionuclides and are thus more penetrating than most gamma-ray emissions. The dose rate at 1 m above the soil due to contamination in the uppermost 15 cm is $7.25 \times 10^{-17}$ [Sv/s]/[Bq/$m^3$], however, the dose rate at 1 m above the soil due to contamination from all the soil deeper than 15 cm is only $1.43 \times 10^{-17}$ [Sv/s]/[Bq/$m^3$] (Eckerman and Ryman, 1993) (i.e., contamination in the uppermost 15 cm of soil accounts for 84 percent of the exposure) (Note: 1 Sv = 100 rem and $3.7 \times 10^{10}$ Bq = 1 Ci). The degree of self-shielding would increase for radionuclides whose gamma ray emissions are less energetic. There are at least two processes by which radionuclides originally spread on the soil surface (e.g., by irrigation with radioactively contaminated groundwater) can become distributed to lower soil layers, effectively removing them from the biosphere unless they reach the water table. The first process is manual redistribution by plowing (e.g., the plowed layer is deeper than the root zone for the particular crop grown in that soil). The second process is leaching of radionuclides from surface layers. Water falling on the soil surface, caused by irrigation or precipitation, has the potential to infiltrate to deeper soil layers. During the infiltration process, the percolating groundwater may carry some of the surface contamination with it into the deeper soil layers, depending on such factors as the radionuclide solubility and distribution coefficient. It is noted that these processes may work in conjunction, meaning that radionuclides would be removed more rapidly due to both processes than either process acting alone. However, leaching of a contaminated tephra deposit could result in transport of radionuclides to the underlying groundwater system, especially in areas such as Fortymile Wash. During periods of flooding, the amount of water that would percolate downward could provide a mechanism for contamination of the groundwater system.




* Relationships in bold are identified in the text

**Figure 17. Diagram of the relationships between "redistribution of radionuclides in soil" and other integrated subissues**

If a volcano should erupt through a repository at YM, the volcanic material could be deposited in the Fortymile Wash drainage basin. The initial tephra deposit will be subject to some amount of redistribution from near surface winds. Following deposition, the materials will be subjected to surface processes such as erosion. While it can be assumed that the drainage basin is in a quasi-steady state at present, the tephra deposit would put the system out of equilibrium and be the most likely material to be eroded. If it is assumed that the volcanic characteristics are similar to Lathrop Wells cone and that the tephra deposit has a half-life of 1000 years (U.S. Nuclear Regulatory Commission, 1999d), during the first 1000 years after the eruption approximately $10^7$ $m^3$ of material would be eroded from the tephra deposit and transported downstream. Examination of the geomorphic characteristics of Fortymile Wash demonstrates that this wash goes from an erosional regime to a depositional regime just north of Highway 95. The fines from these freshly deposited materials are quite susceptible to wind erosion; one of the more likely results of such natural activity would be to increase the amount of resuspendable material available for inhalation around the deposition point. Flooding of Fortymile Wash is a periodic process. Therefore, every few years this process would be repeated, continually depositing fresh material (i.e. uncontaminated soil and radioactively contaminated tephra) in the area of the critical group.

While the fresh tephra deposit would be expected to be the source of a potential peak dose from an igneous event, the calculation of expected annual dose requires the evaluation of the potential exposure over time from disruptive events (see Section 4.4.1). The effect of leaching of radionuclides into the groundwater and erosion, transport and deposition of surface material in the area of the critical group would not likely produce a dose as large as the dose in the year following the eruption. However, it could be significant in evaluating total dose over time. This is an area, therefore, that needs to be evaluated by DOE.

Staffs from NRC, CNWRA, DOE, and the State of Nevada conducted numerous investigations regarding the probability and likely consequences of repository disruption by basaltic IA. Intersection of the repository by a volcano with resulting direct release of the material to the accessible environment, is the scenario that NRC has spent the most effort analyzing because it appears to be the most significant from a dose- or risk-based perspective. It is assumed that an extrusive basaltic volcanic event will incorporate radioactive waste into the ascending magma and transport it to the critical group location. Historically active basaltic volcanoes are capable of dispersing tephra particles >0.1-mm diameter at least 30 km from the vent, resulting in 1- to 100-mm thick deposits (Hill, et al., 1996). The redistribution of these radionuclides in the soil after deposition on the ground is an important process to determine the dose impacts to a member of the receptor group from an igneous event both in the year of the eruption and in following years. Thus, the processes associated with the redistribution of radionuclides in soil are important in determining the risk associated with IA disrupting the repository.

The amount of contaminated ash resuspended from the fall deposit was shown to be very important to calculating volcanism dose, as there is a nearly linear relationship between dose and airborne mass-loading factor. In addition, about 90 percent of the dose from volcanism is caused by inhalation of contaminated ash. In the proposed 10 CFR Part 63 rule, the expected annual dose is used to determine compliance with proposed performance objectives. Expected annual dose is the dose weighted by probability of event occurrence (i.e., risk), with the maximum expected annual dose during the postclosure period used to determine compliance. The calculation of expected annual dose is strongly influenced by the evolution of the RNs in the tephra deposit over thousands of years following the eruption. The annual dose from these residual tephra deposits would likely be less than the peak dose acquired during the first year of the eruption, due to removal of fine-ash particles, deposit erosion, and radioactive decay.

#### 4.3.3.1.3 Lifestyle of the Critical Group

The discussions and technical basis on the lifestyle of the critical group abstraction in this section are current as of the VA documentation. The next revision of this IRSR will provide an update of NRC's technical basis for the staff review consistent with the current design and knowledge of site conditions.

The characteristics of the critical group and related dose calculations are influenced by the biosphere conditions and the characteristics of the radioactive contamination that enters the biosphere through various transport processes such as SZ flow following a postulated groundwater release and airborne fallout resulting from a potential volcanic event. This ISI is derived from the dose calculation component of the biosphere subsystem (Figure 3). The relationships between lifestyle of the critical group and other ISIs are illustrated in Figure 18.

The scope of the lifestyle of the critical group ISI encompasses key aspects of critical group dose calculations based on estimated radionuclide concentrations in the biosphere. In performance assessment calculations, when modeled groundwater or air contaminants reach the location of the critical group, the fate of the contaminants and resulting human health consequences must be estimated by considering characteristics of the biosphere and critical group. The critical group is a hypothetical group of persons, based on characteristics derived from local populations, that is likely to receive the highest exposures from releases of radioactive material to the biosphere. The reference biosphere is the local environment with enough spatial extent to encompass where the critical group resides and how it interacts with materials contaminated by releases from the repository.

Processes related to RT through fractured rock (RT3) involve data and assumptions about transportable chemical species. These processes should support assumptions made for the initial chemical species in the biosphere, to the extent possible. In addition, consequences of IA2 determine the extent and characteristics of contamination from postulated volcanic events that can impact the types of exposure pathways and modeling assumptions applied to the reference biosphere and critical group dose calculations.

Features and processes related to USFIC, such as future climate change (USFIC1), hydrologic effects of climate change (USFIC2), rate of shallow infiltration (USFIC3), and ambient flow in the SZ with dilution (USFIC5), can impact the biosphere and critical group assumptions.

Factors that affect the onset of climate change and the magnitude of climate change, for example, must be considered for hydrologic transport and biosphere modeling of pluvial conditions. Variables related to shallow infiltration such as precipitation and evapotranspiration must also be considered in a consistent manner when modeling leaching of radionuclides deposited on soils in the biosphere. Variables related to dilution analyses such as pumping rates and well technology should be consistent with critical group assumptions, to form a coherent geosphere/biosphere interface.

The ISI for lifestyle of the critical group is directly related to repository performance. Parameters associated with the lifestyle of receptor groups and the biosphere in which they exist, enable performance assessors to transform groundwater and ground surface radionuclide concentrations to a common performance indicator, individual doses. The biosphere dose conversion factors (BDCFs) used in performance assessment dose calculations (that convert water and soil radionuclide concentrations to dose) are based on assumptions about the lifestyle of the critical

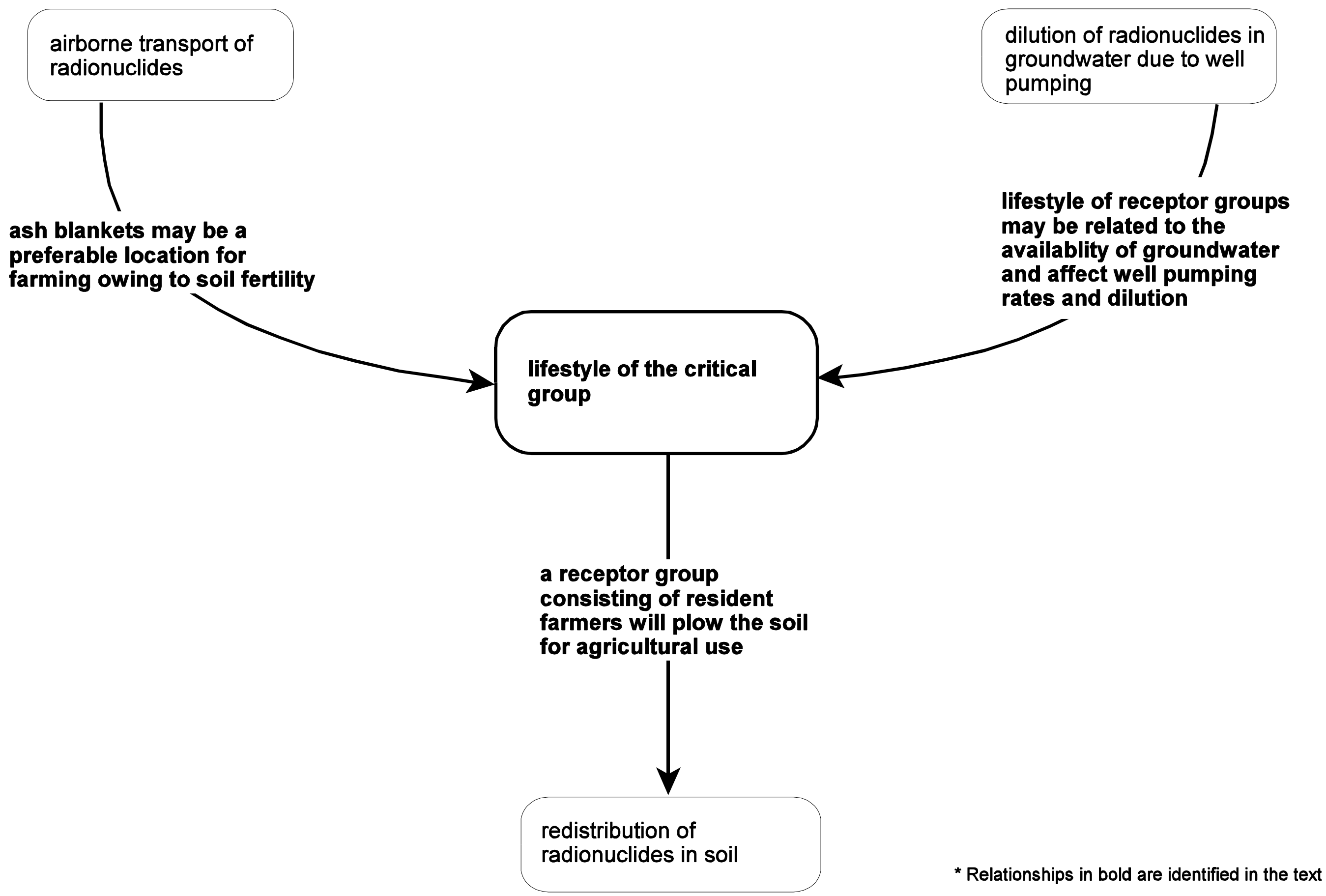



**Figure 18. Diagram of the relationships between "lifestyle of the critical group" and other integrated subissues**

group. BDCFs proportionally affect performance assessment dose results, and assumptions about the critical group and biosphere can thereby significantly affect the magnitude of the calculated dose.

Past NRC/CNWRA uncertainty analysis of the BDCFs (LaPlante and Poor, 1997) indicates the range of BDCFs produced when input parameters are sampled from known or estimated distributions spans about an order of magnitude and approximates a truncated log-normal distribution. DOE uncertainty estimates are consistent with these results. This variation suggests that assumptions and supporting data for dose conversion factor (DCF) calculations can have a significant impact on calculated doses. While no analyses have been conducted to date by CNWRA to quantify the importance of this ISI relative to others, DOE analyses suggest the BDCFs that result from this ISI are of moderate importance to postclosure performance (U.S. Department of Energy, 1998a). Moderate importance means uncertainty in the DCF contributes a factor of 5–50 increase or decrease in peak dose from the expected value.

The following is an example of possible important physical phenomena and couplings with other ISIs (see Figure 18) :

- RT through the UZ (RT/GS3) requires assumptions about chemical species likely to be transported so that retardation coefficients can be determined. The internal dose factors used to convert radionuclide intakes to dose also rely on general chemical classifications of the radioactive materials ingested by the critical group. Both assumptions should be checked for consistency.

- Quantity and chemistry of water contacting waste (EBS3) involve consideration of present-day infiltration, which is dependent on precipitation and evapotranspiration conditions. Precipitation and evapotranspiration are also parameters that influence the leach factors for the dose conversion calculation that affect removal of radionuclides from surface soils. These assumptions should be checked for consistency.

- Airborne transport of radionuclides (GS7) includes assumptions regarding the particle sizes of air-transported ash/radionuclides to the location of the critical group. The lifestyle of the critical group subissue (BS3) incorporates a mass loading factor for the ash/radionuclide material into the dose calculations. The mass loading factor is based on a number of variable parameters including the particle size of the ash/radionuclide material and perhaps the thickness of the ash blanket. These assumptions should be checked for consistency to the extent practicable.

In their recommendations to the EPA for developing HLW standards for Yucca Mountain, the NAS (National Research Council, 1995) advocated use of the critical group approach. This approach is similar to what had been previously described by the International Council on Radiological Protection (ICRP) (1977, 1985). A critical group was described by the ICRP (1977, 1985) as a relatively homogenous group of people whose location and lifestyle are representative of those individuals expected to receive the highest doses as a result of discharges of radionuclides. The critical group exists in an environment defined by pertinent site-specific conditions referred to as the reference biosphere (an abstraction of the actual biosphere for modeling purposes). The NAS specifically recommended use of the average member of the critical group as the individual dose receptor whose dose (or risk) should be estimated in TSPAs for the proposed YM repository. The NAS also stated that the critical group should be based on cautious but reasonable assumptions. In the proposed HLW standard in 10 CFR Part 63, the NRC adopted the reference biosphere and critical group approach based on cautious but reasonable assumptions. As a result, it is expected DOE's LA will provide the necessary and sufficient information to support the important assumptions regarding the reference biosphere and critical group not explicitly specified in the proposed NRC regulations.

The acceptance criteria for this ISI emphasize the key aspects of biosphere modeling that are important for assessing if the abstraction is adequate and whether relevant NRC requirements have been met (e.g., sufficiency of data, defensibility of parameter selections and assumptions, use and comparison of results with alternative conceptual models, and verification of calculations). Review methods have been formulated to focus on those aspects of the abstraction that prior sensitivity studies have shown are important to performance (LaPlante, et al., 1995; LaPlante and Poor, 1997) and relevant to the proposed NRC requirements for 10 CFR Part 63.

NRC and the CNWRA have been analyzing issues related to the critical group abstraction for several years. An initial report was completed in 1995 (LaPlante, et al., 1995), which documented available parameter information to support conceptual models and parameters for a YM site-specific dose calculation. Subsequently, this report was updated with additional local and regional information to support parameter and model selections and a more detailed sensitivity analysis to assess the importance of parameters (LaPlante and Poor, 1997). NRC also recently published a NUREG report that contains additional information supporting the selection of critical groups (Holonich, 1999). NRC/CNWRA investigations on the lifestyles of potential receptor group members have focused on the average individual member of two possible receptor groups, one with a lifestyle similar to alfalfa farmers currently residing in the Amargosa Desert region and one with a residential lifestyle whose exposure pathways are limited to water consumption (LaPlante and Poor, 1997; Sagar, 1997). These lifestyles, while not encompassing all possible lifestyles in the area, are thought to yield information about the range of doses in the area when used in PA.

The biosphere is defined as the environment in which the critical group exists, and the description of the biosphere includes details such as where and how people obtain their food and climate conditions. Climate impacts the selection of lifestyle parameters such as the types of crops being farmed, water use practices, and length of the growing season. These parameters, particularly those for water usage, can significantly impact the magnitude of BDCFs used in performance assessments. The current biosphere has a climate that is classified as arid on the Koeppen-Geiger climate classification scheme (Strahler, 1969) with a MAT of 61 °F and a MAP of 5.9 inches. (Wittmeyer, et al., 1996). Recent studies indicate that the climate in the YMR may experience an increase in MAP ranging from about 40 percent to as much as 3 to 5 times current MAP (DeWispelare, et al., 1993; U.S. Nuclear Regulatory Commission, 1999h) during the 10,000-year period and beyond. These same studies indicate that the MAT may experience a decrease ranging from about 3 °F to as much as 18 °F. Even a change in the climate corresponding to the low end of these ranges would reclassify the YMR as semiarid in the Koeppen-Geiger climate classification scheme. The interval in time when such changes are estimated to occur is known as a pluvial period.

CNWRA has performed a preliminary analysis on the possible changes in the receptor group lifestyles in a pluvial biosphere at YM (LaPlante and Poor, 1997). Results suggest the general characteristics that define the two receptor groups previously profiled (alfalfa farmer, resident) are not expected to change to a great degree in a pluvial biosphere, although changes are possible in the magnitude of some practices, such as the amount of irrigation water used in a season.

## 4.4 DEMONSTRATION OF THE OVERALL PERFORMANCE OBJECTIVE

NRC published a proposed rule to be applied to the Yucca Mountain repository, 10 CFR Part 63 (U.S. Nuclear Regulatory Commission, 1999a). Demonstration of compliance with the overall performance objective must be supported by DOE's PA, which includes demonstration of multiple barriers (Section 4.1), treatment of scenarios (Section 4.2), and treatment of model abstraction (Section 4.3). The final requirements for the overall performance objective will be established after the rule is published in final form, and the acceptance criteria in the YMRP will be modified (as needed) to be consistent with the final regulations.

Acceptance criteria have been developed in the following areas: (i) calculation of expected annual dose, (ii) demonstration that expected annual dose does not exceed regulatory limits; (iii) confidence in TSPA results, (iv) human intrusion, and (v) comparison of alternative design features. The technical basis is provided.

### 4.4.1 Calculation of Expected Annual Dose

For staff to determine whether the DOE TSPA has demonstrated that the repository system will meet the dose limit in proposed 10 CFR 63.113, DOE must provide the results of the TSPA in a properly calculated expected annual dose curve.

In the process of conducting the TSPA, DOE will perform a scenario analysis to determine which scenarios can be screened on the basis of probability or consequence in accordance with 10 CFR Part 63. At the conclusion of the scenario analysis process, a number of disruptive scenario classes will be identified that must be analyzed in addition to the base scenario class. To appropriately calculate the risk from the repository system and ensure that the risk is not underestimated, the expected annual dose curve must include the contribution from all unscreened scenario classes.

The contribution to the expected annual dose from each of the scenario classes must incorporate both the probability and consequence of the scenario class. One appropriate method for the incorporation of both the probability and consequence of the scenario class is to multiply the conditional dose history for the disruptive scenario classes (i.e., given that the disruptive event occurs) by the probability that the scenario class occurs at any time during the calculational time period. These probability-weighted conditional dose histories can be added to the dose history for the undisturbed case, which can be weighted by the probability that no disruptive events have occurred during the scenario. The section that follows provides an example of an expected annual dose calculation.

#### 4.4.1.1 Sample Expected Annual Dose Calculation

Acceptance criteria associated with the calculation of the performance measure—consistent with parameter uncertainty, alternate conceptual models, and the treatment of processes and events—have not been included in this revision of the TSPAI IRSR. In the absence of such acceptance criteria, one acceptable approach for calculating the expected annual dose to the average member of the critical group is provided for informational purposes. The basic steps used to calculate the expected annual dose are described. These steps are then illustrated with a simple example that follows the NRC approach using a Latin Square method of developing mutually exclusive scenario classes (see Cranwell, et al., 1990).

The sequence of calculations proceeds as follows:

Step 1 All parameters that are defined through their probability distributions are sampled. If there are *M* such parameters and *N* parameter combinations are to be simulated, then the sampling operation provides *N* vectors, each containing *M* values. This process is repeated for *K* scenario classes in addition to the basecase.

Step 2 A simulation is performed for each of the *N* vectors for the basecase. Simulations are also performed for each of the *K* scenario classes including disruptive events for a series of *L* times of occurrence for the disruptive event associated with the scenario class. No restriction requires the same number of vectors to be evaluated for each scenario class. These simulations are used to determine the mean dose history for all times following the event assuming that the disruptive event occurred at time *L*. The scenario class expected annual dose for each scenario class is calculated using the following formulae:

For all disruptive scenario classes:

$$R_{SC}(t) = \sum_{n-1}^{E} (1 - e^{-p\Delta T})D_n(t)$$

where, *R(t)* is the scenario class expected annual dose at time *t,* ρ *T* is the increment of time associated with event *n* (in years), *p* is the annual probability of event, $D_n(t)$ is the mean annual dose from event *n* at time *t*, and *E* is the number of times of event occurrence for which mean dose histories are calculated.

For the basecase scenario class:

$$R_{BC}(t) = D(t)(1 - \sum_{i-1}^{K} 1 - e^{-p_i t})$$

where $\rho_i$ is the annual event probability of event and *i* and *K* are the number of scenario classes.

Step 3 The results from Step 2 then are combined. Each scenario has an associated scenario-expected annual dose curve. The expected annual dose to the average member of the critical group is the sum of the scenario expected annual dose curves. This curve of the expected annual dose represents the expected risk from the repository over time.

The following example illustrates the steps described previously. This example demonstrates the calculational methodology only, and the values of dose and risk used in the example do not necessarily represent expected system performance. Assume that the annual probability of occurrence of scenario class **Θ** is 5 × $10^{-6}$ per year, and the annual probability of occurrence for scenario class **Ψ** is 1 × $10^{-7}$ per year. The scenario class **{ΘΨ}** is screened out on the basis its probability of occurrence (5 × $10^{-13}$ per year) is less than $10^{-8}$ per year, so the consequence analyses of only the basecase and two scenario classes based on disruptive events are to be performed; that is, *K* = 2, and the probability of ***{ΘΨ}*** is added into the scenario ***{Θ¯Ψ}***. Also assume that the scenario expected annual dose time history for the basecase performance of the repository is as shown in Figure 19. Figures 20 and 21 show the dose history for scenario classes **Θ** and **Ψ**, respectively, for a variety of times of occurrence for the disruptive event associated with

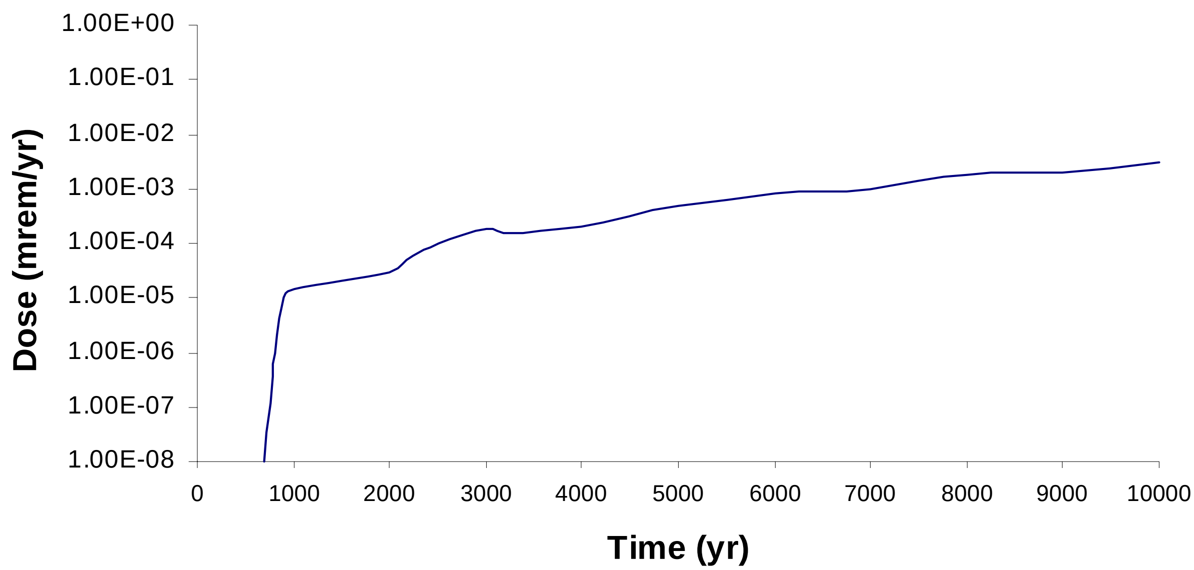



**Figure 19. Mean dose history for the basecase performance of the repository**

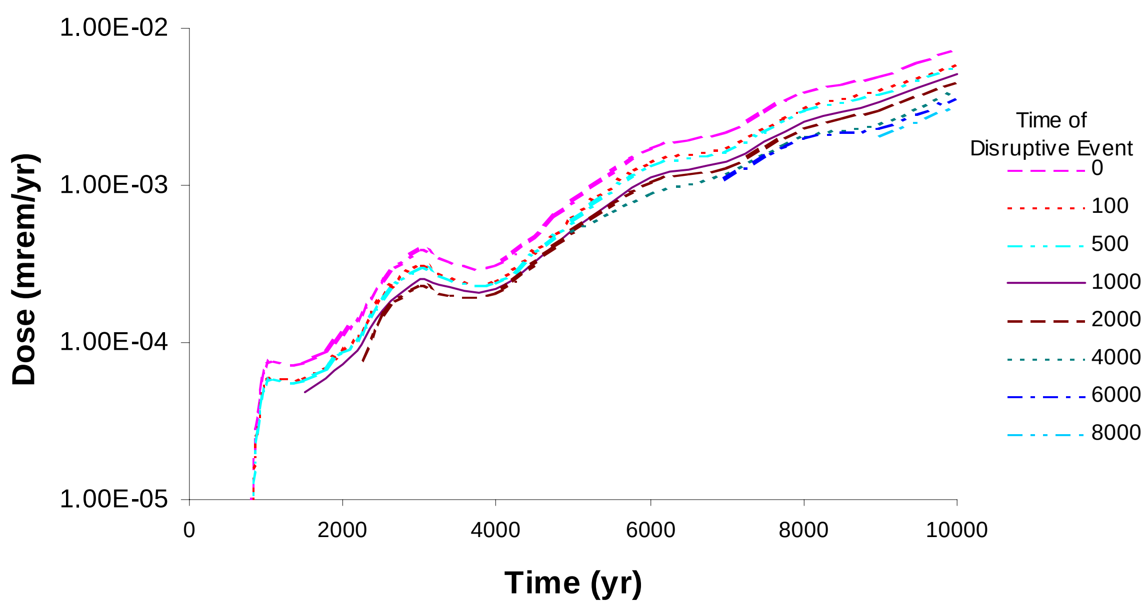



**Figure 20. Scenario class dose history for scenario class Θ based on time of occurrence of the disruptive event**

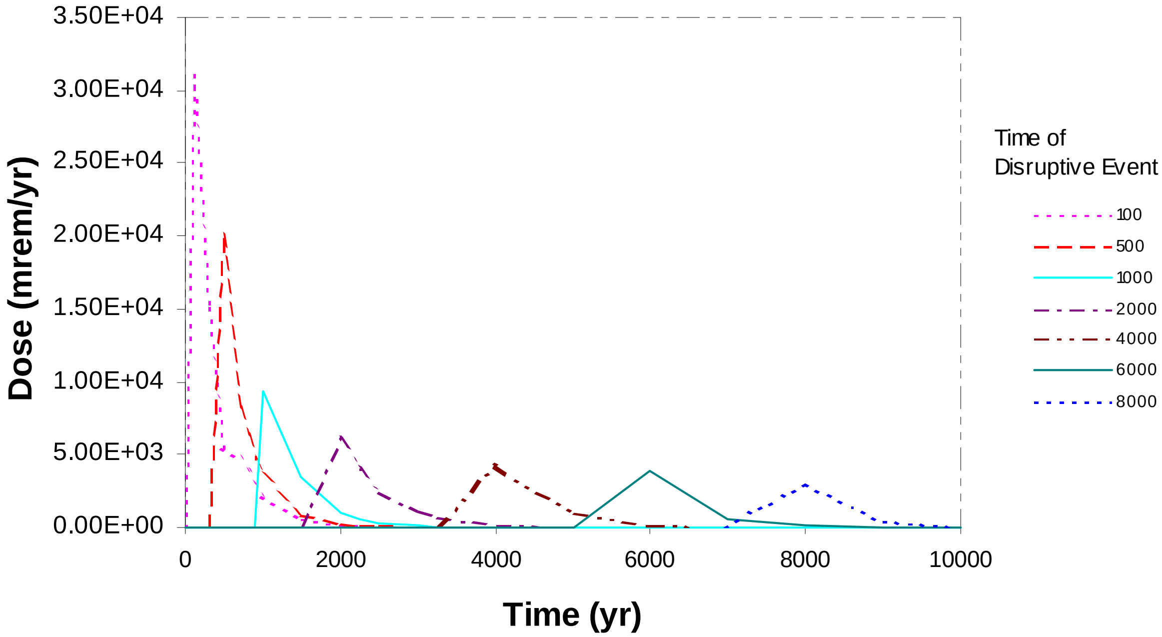



**Figure 21. Scenario class dose history for scenario class Ψ based on time of occurrence of the disruptive event**

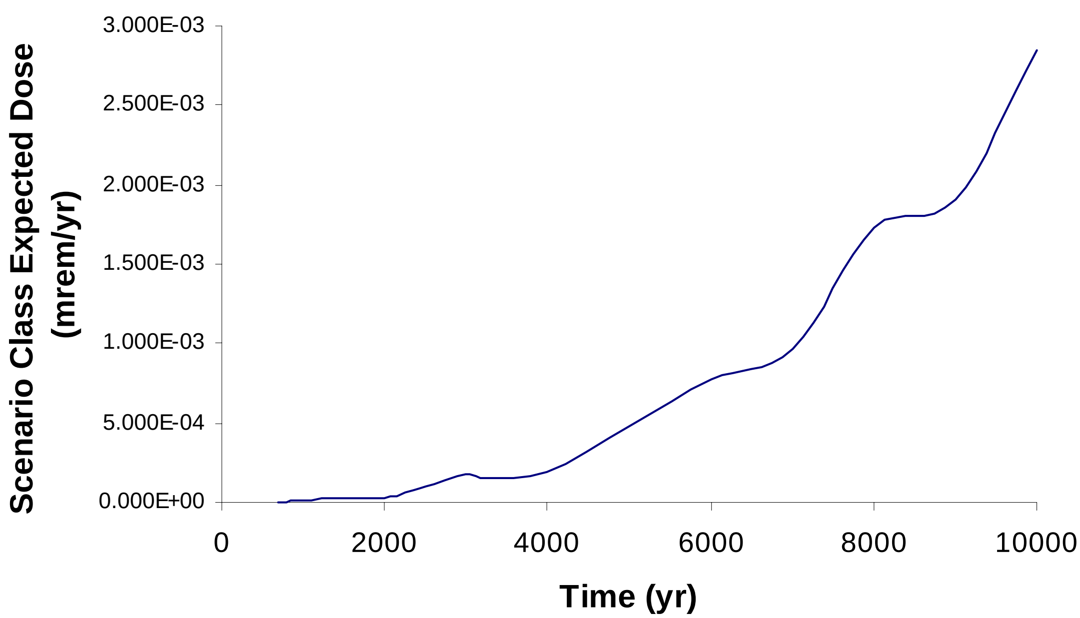



**Figure 22. Scenario class expected dose history for basecase**

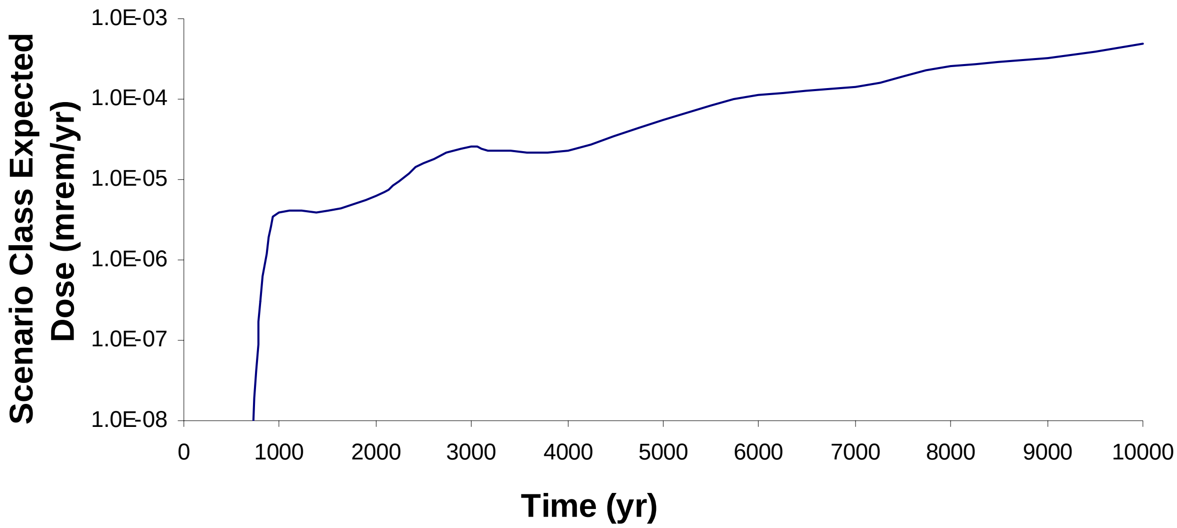



**Figure 23. Scenario class expected dose history for scenario class Θ**

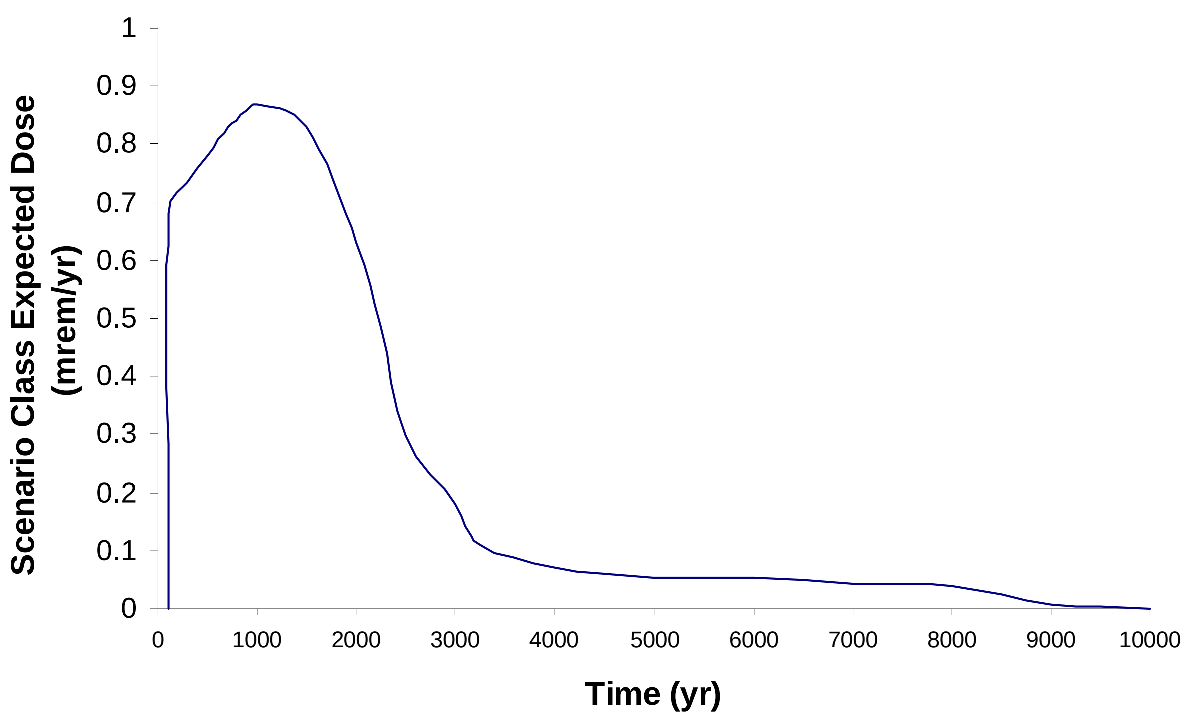



**Figure 24. Scenario class expected dose history for scenario class Ψ**

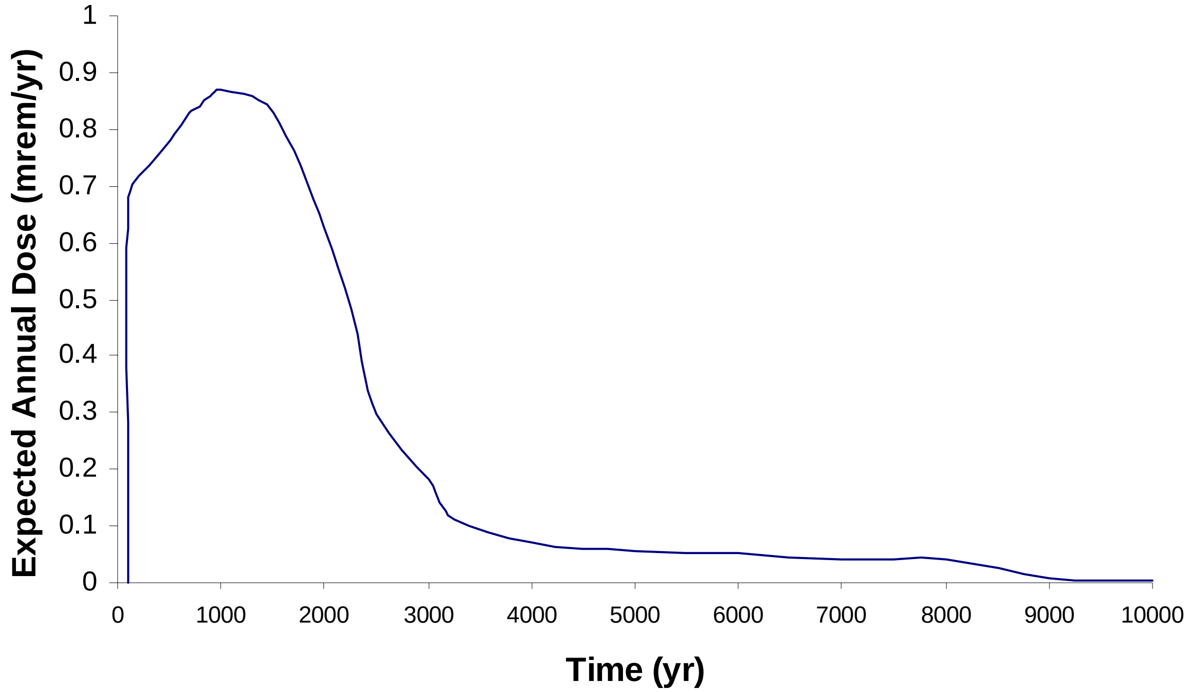



**Figure 25. Expected Annual Dose**

that scenario class. Figure 22 shows the scenario class expected annual dose for the basecase scenario. Figures 23 and 24 show the scenario class expected annual dose history for scenario classes **Θ** and **Ψ**, respectively.

Figure 25 shows the summation of the expected annual dose curves of these three scenario classes. Because the probability of occurrence of the disruptive event associated with each scenario class was included in the calculation of the scenario expected annual dose, the final expected annual dose curve is simply the sum of the three curves at all times. This curve represents the expected risk (with time) from the repository.

### 4.4.2 Demonstration that Expected Annual Dose does not Exceed Regulatory Limits

The use of a probabilistic methodology to calculate the performance of the repository system requires a sufficient number of realizations be conducted to ensure that the results of the calculation are stable if additional realizations are run. Frequently, in calculations such as these, the mean is driven by a relatively small number of high-consequence realizations that occur because several parameters are sampled towards the end of their distributions. Because the performance measure of interest based on the proposed 10 CFR Part 63 is the peak of the expected annual dose curve, it is necessary to demonstrate that the mean results do not change when additional realizations are completed.

Providing support for the DOE TSPA code is related to the concept of code validation in NUREG–0856 (U.S. Nuclear Regulatory Commission, 1983). However, true validation of the DOE TSPA code is not possible because there are no data on an actual repository system against which the results of the DOE TSPA code may be compared. Therefore, support for the DOE TSPA code must come from other sources to provide confidence that the code appropriately represents or bounds the projected performance of the repository system. Other sources of support could include comparison of the results against the results of other computer codes developed to assess the performance of the YM repository system (i.e., Mohanty and McCartin, 1998, or Electric Power Research Institute, 1998) or providing sufficient transparency and traceability in the assessment results that a reviewer is able to perform simple confirmatory calculations to demonstrate that the results of the DOE TSPA are reasonable.

### 4.4.3 Confidence in Total System Performance Assessment Results

To have confidence that the results of a computer model accurately portray the physical processes that it is intended to reproduce, the computer model must be verified to ensure that the model is correctly implementing the numerical models and also must be supported to provide confidence that the numerical models provide an adequate representation of the actual physical processes. Software verification is typically performed through code testing, analysis of intermediate outputs, sensitivity analyses, and other similar methods. In addition to verification of the individual process-level models, there must be confidence that the entire DOE TSPA code properly links these individual process-level models and provides a realistic representation of the performance of the repository system. Verification of the TSPA code will ensure that data are properly transferred between code modules.

The concept of uncertainty in risk when expressed as a distribution of aggregate risk estimates must be understood to correctly use the risk results. The distribution represents the uncertainty in the parameters and models of the PA. The method by which the PA is performed influences the results because the assumptions, inputs, and models used in the PA may introduce numerical artifacts into the analyses. Defining parameter distributions that are narrower than the data warrant can significantly bias the results of the PA, even when the mean of the distribution remains the same. In particular, threshold phenomena may lead to relatively high doses, which could not be reflected in the TSPA output if parameter ranges are defined too narrowly (U.S. Nuclear Regulatory Commission, 1994). Although the mean estimate of the risk is used to implement the quantitative objectives of the regulation, the Commission has indicated that license applicants must quantify and understand those important uncertainties involved in risk predictions. Proper attention must be given not only to the range of uncertainty surrounding the probabilistic estimates, but also to the phenomenology that most influences the uncertainties. Therefore, sensitivity studies should be performed to determine those uncertainties most important to the probabilistic estimates (Ward, 1992).

The scheme used to sample the value of uncertain parameters in the code is closely related to the number of realizations needed to achieve a stable mean. The two most widely used sampling schemes for uncertainty propagation are Monte Carlo Sampling and Latin Hypercube Sampling. Both methods are conducted by determining probability distributions for all input variables and randomly selecting values from these distributions to form sets of inputs. Monte Carlo Sampling uses a simple random sampling technique that selects values from the parameter distributions based solely on their distribution shape. This procedure allows complete flexibility in the selection of input distributions and is easy to implement, but makes it difficult to obtain accuracy in the tails of output distributions. If several parameters have highly skewed distributions, a high number of realizations need to be conducted to ensure that the tails are properly sampled and represented in the output distribution (U.S. Nuclear Regulatory Commission, 1994). Latin Hypercube Sampling (Iman and Shortencarier, 1984) is a stratified sampling technique developed to improve on the efficiency of Monte Carlo Sampling. Prior to selecting values from the input distributions, the probability distribution of each input variable is divided into discrete intervals, where each interval has an equal probability of occurrence. Each interval is then sampled an equal number of times, although each selection within an interval is randomly obtained. This procedure ensures that all parts of a distribution are sampled and generally requires a much smaller sample size to achieve the same accuracy in the mean value as simple random sampling (U.S. Nuclear Regulatory Commission, 1994).

### 4.4.4 Human Intrusion

The requirements for the human intrusion analysis are specified in proposed 10 CFR 63.113(d). The basis for the requirements for the human intrusion analysis is located in the Statements of Consideration for the proposed 10 CFR Part 63 (U.S. Nuclear Regulatory Commission, 1999a).

### 4.4.5 Comparison of Alternative Design Features

To demonstrate compliance with the requirements of proposed 10 CFR 63.21(c)(7), DOE must provide a comparison of the performance of the repository system using alternatives to the major design features.

The requirement to perform a comparison of alternative design features is specified in proposed 10 CFR 63.21(c)(7). The basis for the requirement to perform a comparison of alternative design features is located in the Statements of Consideration for proposed 10 CFR Part 63 (U.S. Nuclear Regulatory Commission, 1999a).

## 5.0 STATUS OF ISSUE RESOLUTION AT THE STAFF LEVEL

This section has been updated to reflect the current status of issue resolution within the TSPAI KTI. All four TSPAI subissues (System Description and Demonstration of Multiple Barriers, Scenario Analysis, Model Abstraction, and Demonstration of the Overall Performance Objective) are currently open. The source of the open status is discussed in detail for each subissue.

An Open Item is resolved at the staff level when the staff has no further questions or comments at a point in time regarding how DOE's program addresses the item. Otherwise, its status and progress would be followed until its resolution during the licensing process. Note that resolution is a tentative judgment at a point in time during the prelicensing consultation period. The basis for resolution may change as new data, conceptual approaches, methods, or codes are developed, and their significance to performance is assessed. Consequently, the status of the resolved items may change, and new Open Items may be added. The Open Items related to TSPA are listed in this section. NRC will continue to interact with DOE on issues related to TSPA and will close Open Items as appropriate. In addition, some Open Items may be resolved as no longer relevant when new regulatory requirements for the disposal of HLW at YM are promulgated.

The initial identification of issues (i.e., Open Items) related to DOE's scenario analysis methodology was conducted following the staff's review of DOE's mandatory SCP (U.S. Department of Energy, 1988). In its review of the SCP, 357 Open Items (questions, comments, and concerns) were identified in NRC's *Site Characterization Analysis* (see U.S. Nuclear Regulatory Commission, 1989). Of these, 16 were scenario-related. As a result of the prelicensing consultation process between DOE and the NRC staff in the intervening years, ten of these scenario-related Open Items were resolved at the staff level. The status of the resolution of TSPAI Open Items is summarized in Table 1, including scenario-related Open Items. Identification and resolution of issues in model abstraction are primarily contained in the issue resolution status reports of the process KTI's.

Table 4 includes a summary of discussion points that have been raised at recent DOE/NRC Technical Exchanges. These discussion points are discussed in the sections identified in Table 19 of the previous revision of this document. The discussion points are being tracked by other KTIs, are no longer considered major areas of disagreement between NRC and DOE staff, or have been turned into Open Items. As such, it is not necessary to continue to track these items as discussion points in this IRSR.

## 5.1 SYSTEM DESCRIPTION AND DEMONSTRATION OF MULTIPLE BARRIERS

### 5.1.1 Transparency and Traceability

The review for transparency and traceability focuses on whether the DOE analysis is sufficiently clear for reviewers to understand the approach and the results of the TSPA. The DOE analysis should be sufficiently transparent to clearly identify methods to test the accuracy and reproducibility of the results. The analysis should be transparent to ensure that the DOE meets the normal requirements for technical explanations, proof of authenticity, and legitimacy of actions. The analysis should also be traceable, such that there is an unbroken chain linking the results of an assessment with models, assumptions, expert opinions, and data used in the formulation of the result. The review for transparency and traceability will also focus on whether the use of risk insights by the DOE is sufficiently clear and understandable. The documentation should clearly present how risk insights were utilized in development and implementation of the PA.

**Table 4. Discussion points identified in recent U.S. Department of Energy/U.S. Nuclear Regulatory Commission performance assessment technical exchanges**

| | Questions | Discussion |
|---|---|---|
| TE1 | What is meant by DOE's definition of "importance sampling" and what approach will be used to determine importance? | See TSPAI IRSR, Rev. 2 |
| TE2 | How will the results of sensitivity analyses be used and integrated into DOE's TSPA? How does DOE define parameter variability and parameter uncertainty? How are they different from each other? How will they be treated in TSPA-VA? How will parameter variability and uncertainty be propagated through the sequence of models, given that some models will be calibrated? How will sensitivity to performance from the near-field environment be assessed in TSPA-VA? | See TSPAI IRSR, Rev. 2 |
| TE3 | How is DOE calibrating its use of abstracted data and response surfaces from process-level modeling results in the performance assessment calculations? | See TSPAI IRSR, Rev. 2 |
| TE4 | What radionuclides will DOE use for its dose calculations? How has DOE screened radionuclides from inclusion into the dose calculation? | See TSPAI IRSR, Rev. 2 |
| TE5 | How will DOE represent results from alternative conceptual models? | See TSPAI IRSR, Rev. 2 |
| TE6 | Possible early source term releases from the repository may overlay flow-fields with fast pathways. These relationships need to be preserved when evaluating performance. DOE does not believe that there is a need to preserve these relationships. | See TSPAI IRSR, Rev. 2 |
| TE7 | What is DOE's approach to the transport and retardation of radionuclides in alluvium? If DOE takes credit for this retardation, what data will DOE use to support this credit (including the location of the tuff-alluvium boundary)? | See TSPAI IRSR, Rev. 2 |
| TE8 | DOE plans to use a matrix diffusion model in TSPA-VA, supported with data from the C-Well Complex. Alternative interpretations of the C-Well Complex data are possible and will be explored to evaluate the significance of matrix diffusion. How is matrix diffusion being modeled in the UZ and SZ? How much credit will DOE take for matrix diffusion in the saturated zone and in the unsaturated zone? | See TSPAI IRSR, Rev. 2 |
| TE9 | The USGS Regional Groundwater Flow Model shows steep vertical mixing in the saturated zone particle transport model. This is an artifact of the coarseness in the model (see OSC0000001347C102). | See TSPAI IRSR, Rev. 2 |
| TE10 | How is the flow from the saturated zone being represented and treated in the flow and transport model? (See OSC0000001347C102). | See TSPAI IRSR, Rev. 2 |
| TE11 | What is the significance of colloids on performance? | See TSPAI IRSR, Rev. 2 |

**Table 4. Discussion points identified in recent U.S. Department of Energy/U.S. Nuclear Regulatory Commission performance assessment technical exchanges (cont'd)**

| | Questions | Discussion |
|---|---|---|
| TE12 | The upper bound for deep percolation may be much higher than that currently estimated by DOE. What is a reasonably conservative upper bound for deep infiltration and what bound will be used by DOE? | See TSPAI IRSR, Rev. 2 |
| TE13 | DOE believes that it is appropriate to assume steady-state conditions for unsaturated zone flow. Is it appropriate to assume steady-state conditions for the unsaturated zone flow, given the potential impact of climate change? | See TSPAI IRSR, Rev. 2 |
| TE14 | What basis is DOE using to estimate radionuclide concentrations in the aquifer? | See TSPAI IRSR, Rev. 2 |
| TE15 | What basis is DOE using to support its estimates of Neptunium solubility? | See TSPAI IRSR, Rev. 2 |
| TE16 | DOE plans to take credit for degraded WPs. How much credit will DOE take for the contribution of degraded WPs? What technical basis will DOE use to support taking this credit? | See TSPAI IRSR, Rev. 2 |
| TE17 | If DOE is to take credit for galvanic protection, what basis will be used to support this? | See TSPAI IRSR, Rev. 2 |
| TE18 | What data are DOE using to support its modeling of C-22 behavior (e.g., uniform corrosion rate and stress corrosion cracking susceptibility)? | See TSPAI IRSR, Rev. 2 |
| TE19 | What basis is DOE using for establishing and applying the near-field environments for WP corrosion (e.g., corrosion potentials)? | See TSPAI IRSR, Rev. 2 |
| TE20 | How is DOE integrating the interactions between the engineered barrier system and the natural system for radionuclide transport? | See TSPAI IRSR, Rev. 2 |
| TE21 | The primary objective of the concrete liner is to prevent preclosure rock falls. Secondary effects, such as the modification of water chemistry during the postclosure period, could have both positive and negative performance implications. How does DOE plan to address the performance of the concrete lining on repository performance? | See TSPAI IRSR, Rev. 2 |
| TE22 | How are the consequences of seismic events (i.e., vibratory ground motion and rockfall) on WPs going to be evaluated? (See also OSP0000831821Q001). | See TSPAI IRSR, Rev. 2 |

The review for the system description and demonstration of multiple barriers covers the following areas: (i) completeness and clarity of documentation; (ii) description of scenarios; (iii) explanation of model abstractions; (iv) establishment of source and validity of data; (v) assessment results; and (vi) description of TSPA Code Design and Data Flow. The staff review is based on the following set of questions identified under each area of review.

*Completeness and Clarity of Documentation*

- Are the TSPA results traceable to modeling assumptions and input parameters?

- Are modeling assumptions and input parameters traceable to supporting information (e.g., design, site characterization information), analyses, and expert opinions?

*Description of Scenarios*

- Is the screening process for inclusion or exclusion of FEPs fully described?
- Are relationships among relevant FEPs fully described?

*Explanation of Model Abstractions*

- Are the levels and methods of abstraction described completely?

- Has a map been provided to show the conceptual features and processes represented in the abstracted models and the algorithms used to implement them?

- Has an explicit discussion of uncertainty been provided to identify those issues and factors that are of most concern?

*Establishment of Source and Validity of Data*

- Is the origin, sufficiency, and quality of data able to be established (commensurate with importance to performance) from the documentation provided?

*Assessment Results*

- Can PA results be traced back to applicable analyses that identify the FEPs, assumptions, input parameters, and models in the PA?

- Do the PA results include a presentation of intermediate results that provide insight into the assessment?

*Description of TSPA Code Design and Data Flow*

- Are computational modules (e.g., source term, saturated zone) of the TSPA identified and described?

- Is the flow of information within the TSPA code (between modules) described?

#### 5.1.1.1 Description of the U.S. Department of Energy Approach

DOE has described its approach to transparency and traceability in Section 2.6 of TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a). DOE will use graphics and multiple levels of detail in the documentation to ensure that its TSPA is transparent. Traceability will be achieved through the use of configuration control of software and data. The overall approach to providing a transparent and traceable document for the TSPA-SR will involve developing a clear analysis method, followed by development of the text and graphics necessary to meet the objectives. The documentation will be coordinated by technical integrators, technical specialists, graphic specialists, technical editors, and production specialists to ensure that the document is transparent and traceable. Several levels of detail will be used in communicating results, depending on the audience, using graphics and text developed to provide information to the appropriate audience. A progression of documents from complex to simple will be used to satisfy the mix of audiences comprising the various stakeholders and reviewers of the TSPA-SR.

Transparency will be achieved using an easy-to-understand graphical portrayal of the physical processes evaluated by the models. The illustrations showing model conceptualization will be developed with the help of graphic artists and will provide a level of detail appropriate for a technically literate audience unfamiliar with radioactive waste disposal. For clarity of presentation, the analyses will be divided into several parts, each of which has associated key processes. These processes will be displayed graphically.

The text of the TSPA-SR, which will be initially developed by the PA analysts, will be reviewed by a technical editor to ensure that excessive use of acronyms and jargon is avoided. Additionally, multiple levels of review will be conducted to ensure that the documentation meets its goals for transparency and traceablility. Project reviewers will review the text for both appropriateness and technical content. External reviews of the approach and procedures may be solicited, and briefings and comments will be expected from the U.S. Nuclear Waste Technical Review Board and the U.S. Nuclear Regulatory Commission.

Traceability of the analysis will be achieved by explicitly identifying the sources of data, the version of software, and the models. Interested parties will be able to reproduce all steps taken in the analyses without assistance from the DOE PA analysts because explicit documentation will be available of all steps taken in the analysis, of the software, and of the input used to generate the analyses. The top level of the PA model hierarchy is mostly self-contained in the TSPA code and its associated linked files, making reproducibility of the analysis straightforward. The process for linking the process models, the basis of the process models, and the supporting data for TSPA-SR.

At the DOE/NRC Technical Exchange on TSPA on June 6–7, 2000, DOE indicated that it would rely on the GoldSim® software (Golder Associates, Inc., 2000) to provide the transparency and traceability of its analyses. GoldSim® is a graphical, object-oriented computer program. Golder Associates, Inc. (2000) claims that the code can be used to create a model of a proposed system and to identify and understand those factors that control the system. GoldSim® can be used as a system integration tool to link the models of the different subsystems of the repository and also as a visual information management system. It is able to visually integrate input information with the simulation model such that the input for a complex model can be readily accessed by reviewers and viewed along with the analysis results. The program also allows significant flexibility in displaying the analysis results, including intermediate outputs.

#### 5.1.1.2 U.S. Nuclear Regulatory Commission Staff Evaluation

Staff evaluation of transparency and traceability is presented in the sections corresponding to each subissue.

### 5.1.2 Demonstration of Multiple Barriers

The issue resolution review for the demonstration of multiple barriers subissue focuses on the methodology that the DOE will use to demonstrate that the repository system consists of multiple barriers to the release of radioactive materials.

The issue resolution review for the system description and demonstration of multiple barriers covers the following areas: (i) identification of barriers; (ii) description of each barrier's capability; (iii) description of the reliance placed on each barrier; and (iv) technical basis for barriers identified as important to performance. The staff review for issue resolution is based on the following set of questions identified under each area of review.

*Identification of Barriers*

- Are all barriers identified?
- Are there natural and engineered barriers?

*Description of Each Barrier's Capability*

- Is each barrier's capability consistent with the TSPA results?
- What is the impact of the barrier performance on the overall performance measure?
- What is the overall importance of each barrier?
- What are the uncertainties?
- Is the repository system unduly reliant on any single barrier?

*Technical Basis for Barriers Identified as Important to Performance*

- What is the technical basis for the barrier performance and underperformance?
- Is the technical basis commensurate with the degree of reliance placed on a particular barrier and the associated uncertainties?

#### 5.1.2.1 Description of the U.S. Department of Energy Approach

DOE has described its approach to the demonstration of multiple barriers in Section 4.5 of TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a). The multiple-barrier analysis approach will be applied to explicitly identify how the natural and engineered barriers perform. The multiple barrier analysis will use the same modeling framework as the TSPA, except that the scenarios, conceptual models, and parameters are aggregated into barriers, which denote physically distinct components of the system. Examples of these barriers include the waste form, the waste package, engineered barriers within the drift, the UZ, and the SZ. Two approaches will be used in TSPA-SR to demonstrate multiple barriers: (i) a pinch-point analysis and (ii) a neutralization analysis. The pinch-point analysis addresses the issue of how the barriers work, while the neutralization analysis indicates how the overall performance objective changes due to diminished performance credit for a barrier.

The pinch-point analysis processes the output from TSPA calculations at subsystem boundaries, or pinch-points. These pinch points are locations at which mass or energy is being transferred from one subsystem to another. The performance of the barriers will be measured by their abilities to reduce either the radionuclide mass or radionuclide concentration as the nuclides are transported through the barrier. The ability of a barrier to reduce radionuclide mass will be measured by the amount of mass retained in the barrier as a fraction of the initial inventory during the simulation time or the amount of mass retained in the barrier as a fraction of the mass that enters the barrier during the simulation time. Because these values will be calculated probabilistically, the expected value or mean of these quantities will be used to calculate barrier performance. The ability of a barrier to reduce radionuclide concentration will be measured by the ratio of the concentration of radionuclides that exit the barrier to the concentration that entered the barrier. Again, the expected value of these quantities will be used to calculate barrier performance.

The neutralization analysis will be conducted by assuming that one barrier is absent or performing at very pessimistic levels and calculating the performance of the remainder of the system. For each barrier, the performance of the neutralized system is compared to that of the basecase to determine the relative importance of the different barriers by calculating the ratio of the neutralized case to the basecase (Eisenberg and Sagar, 1998). As was done in the pinch-point analysis, the expected value of these quantities will be used as the metric of comparison.

At the DOE/NRC Technical Exchange on TSPA on June 6–7, 2000, DOE indicated that barrier importance would be determined by fixing several parameters associated with either a single barrier or several barrier types (natural or engineered) at their 95$^{th}$ percentile values and running the probabilistic analyses. Some processes that were identified for barrier importance analysis included maximizing infiltration, maximizing seepage for the base infiltration rate, minimizing drip shield lifetime, minimizing waste package lifetime, minimizing cladding lifetime, maximizing radionuclide mobilization and release, minimizing transport times in the unsaturated zone, and minimizing transport times in the saturated zone.

#### 5.1.2.2 U.S. Nuclear Regulatory Commission Staff Evaluation

**AC The barriers relied on to achieve compliance with the overall performance objective, as demonstrated in the TSPA, are adequately identified. The barriers include at least one from the engineered system and one from the natural system.**

STAFF REVIEW:

Based on the Repository Safety Strategy, DOE intends to identify all barriers of the repository system by specifying principal factors and "other" factors. The principal factors are those factors central to demonstrating long-term safety of the repository. The "other" factors, although not contributing strongly to the estimated performance, are factors included in the TSPA that either provide for an additional, but limited, barrier or affect the principal barriers.

STATUS:

Closed. The DOE approach is acceptable.

**AC The capability of the identified barriers to contribute to the isolation of radioactive waste is adequately identified and described such that (i) the uncertainty associated with each barrier's capability is described, (ii) the relationship to assumptions and parameters in the TSPA is clear, and (iii) the degree of reliance placed on each barrier is described relative to each barrier's performance in the TSPA.**

STAFF REVIEW:

The DOE intends to use a pinch-point analysis to describe or demonstrate the capabilities of the repository system barriers. The DOE has described the pinch-point analysis as a method to understand how the barriers act together to provide waste isolation by quantifying specific barrier effectiveness measures (e.g., reduction in radionuclide mass, reduction in radionuclide concentration). This approach is a reasonable method for describing barrier capability provided each of the barriers can be associated with a specific intermediate output or pinch-point of the TSPA. DOE has not explained how uncertainty of barrier performance will be addressed in the pinch-point analysis or how the degree of reliance on each will be described.

STATUS:

Open. The DOE needs to explain its treatment of uncertainty of barrier performance. One approach for treating barrier uncertainty is to include uncertainty in the pinch-point analysis and the uncertainties represented in the pinch-point analysis are discussed relative to the uncertainties included in the TSPA (i.e., model and parameter uncertainty). The DOE also needs to provide a description of its reliance on each of the barriers. This description can be either semi-quantitative (e.g., high, medium, or low reliance) or quantitative (e.g., absolute or relative impact on dose estimates).

**AC A technical basis for assertions of barrier capability is provided that is commensurate with the degree of reliance placed on a particular barrier and the associated uncertainties.**

STAFF REVIEW:

The technical basis for the assertions of barrier capability is anticipated to be documented in the technical basis for the TSPA because the barrier analysis will use the same modeling framework as the TSPA (CRWMS M&O, 1999a). The adequacy of the technical basis will be determined in the relevant reviews conducted for model abstractions and scenarios of the TSPA. However, a fundamental aspect of the support for barrier capability is that the technical basis needs to be commensurate with each barrier's importance to performance. The DOE has not described its method for relating the degree of technical support provided for a barrier to its reliance in the TSPA for demonstrating compliance.

STATUS:

Open. The DOE needs to describe how barrier reliance (or importance) is used to determine the extent of the technical basis needed to support the assertions of each barrier's capability.

## 5.2 TOTAL SYSTEM PERFORMANCE ASSESSMENT METHODOLOGY: SCENARIO ANALYSIS

The review for the scenario analysis subissue, which pertains to the identification of FEPs likely to affect performance objectives, will follow several steps as shown in Section 4.2. The steps include: (i) identification of an initial list of FEPs; (ii) categorization of FEPs; (iii) screening of the initial list of FEPs; (iv) formation of scenario classes using the reduced set of FEPs; and (v) screening of scenario classes. The staff review for issue resolution is based on the following set of questions identified under each review method.

*Identification of an Initial List of FEPs*

- Is the list of FEPs comprehensive based on YM site and regional characterization data and modes of degradation, deterioration, and alteration?
- Is there a defensible explanation for the exclusion of those FEPs identified as irrelevant to the YM setting?
- Is there a systematic approach to develop a comprehensive FEP list? (i.e., documents have been reviewed for indications of why the initial list is believed to be comprehensive)

*Categorization of FEPs*

- Do the categories include each FEP identified in the comprehensive FEP list?
- Is there adequate documentation of the categorization process?
- Does the technical description of FEP categories appropriately synthesize and encompass individual FEPs comprising the categories?
- Are screening rationales consistent with the definitions of FEP categories?

*Screening of the Initial List of FEPs*

- Are the bases provided for nonapplicable FEPs adequate?
- How is the reference design used to screen FEPs (e.g., criticality)?
- Is adequate justification provided for screening events that fall below the regulatory probability criterion?
- Can the probability of occurrence be technically supported?
- Are events inappropriately excluded by defining them so narrowly that the associated probability is below the regulatory threshold?
- Are appropriate criteria used to screen FEPs?
- Are appropriate representative or bounding estimates used for consequence analyses?
- Are coupling of FEPs adequately considered in the screening analyses?

*Formation of Scenario Classes Using the Reduced Set of FEPs*

- Are the resulting scenario classes mutually exclusive in the analysis approach?
- Are the rationales for the formation of scenario classes technically acceptable?
- Do the scenario classes include all possible combinations of events?

*Screening of Scenario Classes*

- Do the technical descriptions adequately support the omission of scenario classes?
- Is there adequate justification provided for screening scenario classes that fall below the regulatory probability criterion?
- Is the probability of occurrence technically well supported?
- Are scenario classes inappropriately excluded on the basis of low probability by defining them too narrowly?
- Will the omission of scenario classes from PA significantly change the magnitude and time of the average annual dose?

This description and the evaluation by NRC/CNWRA of DOE's approach are based on information available to staff as of June 7, 2000. These documents include

- FEP Database (U.S. Department of Energy, 1999a)
- RSS Planning Report (CRWMS M&O, 2000a)
- TSPA-SR Methods and Assumption Report (CRWMS M&O, 1999a)
- AMRs (Seven FEP-related AMRs available May 2000)
- PMRs (Available April 2000)
- Appendix 7 Meeting Handouts (Available March 2000)
- TSPA Technical Exchange Handouts (Available June 7, 2000)

The FEP Database (Swift, et al.,1999) reviewed is an uncontrolled prerelease version. The reviewed AMRs include

- EBS FEPs/Degradation Modes Abstraction (CRWMS M&O, 2000b)
- Engineered Barrier System Features, Events, and Processes and Degradation Modes Analysis (CRWMS M&O, 2000c)
- Evaluation of the Applicability of Biosphere-Related Features, Events, and Processes (FEP) (CRWMS M&O, 2000d)
- Disruptive Events FEPs (CRWMS M&O, 2000e)
- Features, Events, and Processes in SZ Flow and Transport (CRWMS M&O, 2000f)
- Features, Events, and Processes in UZ Flow and Transport (CRWMS M&O, 2000g)
- FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation (CRWMS M&O, 1999b)

The reviewed PMRs include

- Waste Package Degradation Process Model Report (CRWMS M&O, 2000h)
- Biosphere Process Model Report (CRWMS M&O, 2000i)

### 5.2.1 Description of the U.S. Department of Energy Approach

The DOE scenario development process is summarized in Swift, et al. (1999), handouts distributed at the Appendix 7 meeting held on September 8, 1999, and at the DOE/NRC Technical Exchange held June 6–7, 2000. DOE uses five steps for identifying and screening FEPs: (i) FEPs identification and classification, (ii) FEPs screening, (iii) scenario construction, (iv) scenario screening, and (v) implementation of scenarios in the TSPA (Swift, et al., 1999). The first four steps of the approach correspond, though not precisely, to steps outlined in Section 4.2 of this IRSR. DOE's fifth step addresses the same process outlined in Section 4.3 of this IRSR.

The proposed DOE FEPs screening process is summarized in Figure 2 of Swift, et al. (1999). DOE's FEP database is based on an International FEP database (currently with 1261 FEP entries) prepared by the Nuclear Energy Agency (NEA) of the European Commission's Organization for Economic Co-operation and Development (Nuclear Energy Agency, 1997). This database is denoted by DOE as the Global FEP List. The NEA database is a compilation of FEPs from seven nuclear waste disposal programs conducted in five nations and by the NEA. DOE prepared the YMP FEP Database by adding YM site-specific entries to the NEA Database. The site-specific FEPs in the database were identified by a variety of methods, including expert judgment, informal elicitation, event tree analysis, stakeholder review, and regulatory stipulation (Swift, et al., 1999). No specific technique has been identified as a preferred method of FEP identification in the DOE scenario development effort (Swift, et al., 1999). Additional details of the construction process of the YMP FEP database are presented in Chapter 2 of the TSPA-SR Methods and Assumptions document (CRWMS M&O, 1999a). It has been suggested that final demonstration of the comprehensiveness of the YMP Database would be achieved through iterative review and comment (CRWMS M&O, 1999a).

The YMP Database entries have been classified as primary or secondary, with the secondary entries categorized under the 310 primary entries (Swift, et al., 1999). Secondary FEPs are those entries that are redundant (e.g., the NEA list contains as many entries for meteorite impact as there were a number of participating programs) or FEPs that can be aggregated into a single primary FEP for the purposes of the TSPA. Primary entries summarize the information of secondary entries so that screening arguments need to be applied solely to primary FEPs [second box in Figure 2 in Swift, et al. (1999)].

Screening of primary FEPs is based on regulatory relevance and on the basis of probability and consequence [see Figure 2 in Swift, et al. (1999)]. The TSPA disposition of retained FEPs is defined after the screening process. In the DOE approach, each primary entry is intended to have its own screening argument and TSPA disposition.

DOE provided summaries of its preliminary screening results, as presented in Revision 00b of the database, at the September 8, 1999, Appendix 7 meeting. Combined with entries that categorize the primary FEPs, the YMP Database contains 1786 entries. Of the 1786 total entries,

- 796 were classified as "Include"
- 834 were classified as "Exclude"
- 18 were classified as both, meaning that some aspects of the FEP were included and some were excluded
- 138 were undecided (denoted by a blank field or question mark)

With respect to the 310 primary FEPs in the YMP Database

- 167 were classified as “Include”
- 123 were classified as “Exclude”
- 13 were classified as both
- 7 were undecided

The YMP FEP Database (Revision 00b) used in this review is preliminary. In addition, the screening arguments are also preliminary. The DOE informed the NRC at the DOE/NRC Technical Exchange held on June 6–7, 2000, that the FEP list, screening decisions, screening arguments, and TSPA disposition statements have changed substantially. References to the FEP AMRs are expected to be included in the final version of the database.

### 5.2.2 U.S. Nuclear Regulatory Commission Staff Evaluation

The preceding discussion shows that the FEP database partially documents DOE’s effort to meet the scenario analysis requirements. An evaluation of the scenario analysis methodology was presented to the DOE at the DOE/NRC TSPA Technical Exchange held on June 6–7, 2000. The review provides a framework for scenario analysis-related issue resolution, which includes subsequent tracking of database revision and completion together with implementation of the DOE scenario analysis in future prelicensing documents.

At the June 6–7, 2000, DOE/NRC Technical Exchange meeting, DOE indicated that the TSPA-SR document will be very different from the TSPA-LA document. However, because the review criteria developed under the TSPAI IRSR are designed for the LA review, the issue resolution review presented in this section makes no distinction between the TSPA-SR and TSPA-LA review.

In this section, review results and the status of issue resolution pertaining to scenario analysis are presented for each acceptance criterion that NRC will use for reviewing the LA. Results of the review of DOE screening arguments for primary FEPs are summarized in Table 5. This table will be updated at the completion of screening argument evaluation by all KTIs, after which the evaluation status will be changed from “To Be Determined” to “Not Applicable,” “Satisfactory,” or “Unsatisfactory.”

With respect to the scenario analysis items in Table 1, the TSPA-VA (U.S. Department of Energy, 1998a) indicates that DOE has conducted expert elicitations in accordance with NUREG–1563 (Kotra, et al., 1996). An increasing trend in the use of experimental data as opposed to expert elicitation has been noted since the release of the TSPA-VA. At the May 25–27, 2000, DOE/NRC Technical Exchange, DOE indicated its effort toward minimizing the use of expert elicitation (Sevougian, 1999), which is consistent with the trends seen at more recent technical exchanges. Consequently, staff considers items OSC0000001347C009 and OSC0000001347C007 resolved at this time. Similarly, items OSC0000001347C095 and OSC000000134C105 are considered resolved. DOE has identified two scenario classes, nominal and igneous disruption (Swift, 2000), that will be included in the TSPA analysis and used to estimate the repository performance. Staff considers this to be an adequate approach provided that the bases are sufficient for screening other disruptive events (e.g., faulting).

Additional review results for criticality-related FEPs are summarized in Appendix C.  Although review results for criticality FEPs are also presented in other IRSRs, Appendix C is a comprehensive presentation of review results for all criticality-related FEPs.  Additional review results for biosphere-related FEPs are summarized in Appendix D.  FEPS not reviewed by other KTIs are referred to as orphan FEPs, and additional detail of review results are presented in Appendix E.  Although transparency and traceability are treated in a broader sense in Section 5.1, the scenario analysis-specific transparency and traceability is treated in this section.

Areas of deficiency for five acceptance criteria are discussed.  Multiple examples are presented to demonstrate the areas of deficiency.  The selected examples do not constitute a comprehensive list, and more examples may be available in other IRSRs.

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 1.1.01.01.00 | Open site investigation boreholes | E | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.1.01.02.00 | Loss of integrity of borehole seals | E | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.1.02.00.00 | Excavation/construction | E | NA | **TBD** | **U** | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |
| 1.1.02.01.00 | Site flooding (during construction and operation) | E | NA | NA | **U** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.1.02.03.00 | Undesirable materials left | E | **TBD** | NA | NA | **U** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.1.03.01.00 | Error in waste or backfill emplacement | E | NA | NA | **U** | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |
| 1.1.04.01.00 | Incomplete closure | E | **TBD** | NA | NA | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |
| 1.1.05.00.00 | Records and markers, repository | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 1.1.10.00.00 | Administrative control, repository site | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** |
| 1.1.11.00.00 | Monitoring of repository | E | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 1.1.12.01.00 | Accidents and unplanned events during operation | E | **TBD** | **TBD** | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** |
| 1.2.01.01.00 | Tectonic activity - large scale | E | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **S** | NA | NA | NA | NA | NA |
| 1.2.02.03.00 | Fault movement shears waste container | E | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.2.03.02.00 | Seismic vibration causes container failure | E | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.2.05.00.00 | Metamorphism | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 1.2.06.00.00 | Hydrothermal activity | E | NA | NA | **U** | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA |
| 1.2.07.01.00 | Erosion/denudation | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **U** | **U** | **S** |
| 1.2.07.02.00 | Deposition | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **U** | **U** | **S** |
| 1.2.08.00.00 | Diagenesis | E | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.2.09.00.00 | Salt diapirism and dissolution | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 1.2.09.01.00 | Diapirism | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 1.2.09.02.00 | Large-scale dissolution | E | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA |
| 1.2.10.01.00 | Hydrological response to seismic activity | E | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA |
| 1.3.04.00.00 | Periglacial effects | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **U** | **U** | NA |
| 1.3.05.00.00 | Glacial and ice sheet effects, local | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | **U** | **U** | **U** | NA |
| 1.3.07.01.00 | Drought/water table decline | E | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | **U** | NA | **U** | **U** |
| 1.4.01.00.00 | Human influences on climate | E | NA | NA | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | **U** | NA |
| 1.4.01.01.00 | Climate modification increases recharge | E | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA |
| 1.4.01.02.00 | Greenhouse gas effects | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | **U** | NA |
| 1.4.01.03.00 | Acid rain | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | **U** | NA |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 1.4.01.04.00 | Ozone layer failure | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | **U** | NA |
| 1.4.02.01.00 | Deliberate human intrusion | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 1.4.03.00.00 | Unintrusive site investigation | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** |
| 1.4.04.02.00 | Abandoned and undetected boreholes | E | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.4.05.00.00 | Mining and other underground activities (human intrusion) | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 1.4.06.01.00 | Altered soil or surface water chemistry | E | **TBD** | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | **TBD** | NA |
| 1.4.08.00.00 | Social and institutional developments | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | **S** |
| 1.4.09.00.00 | Technological developments | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | **S** |
| 1.4.11.00.00 | Explosions and crashes (human activities) | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **S** |
| 1.5.01.01.00 | Meteorite impact | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** | **U** | **U** |
| 1.5.01.02.00 | Extraterrestrial events | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **U** |
| 1.5.02.00.00 | Species evolution | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 1.5.03.01.00 | Changes in the Earth's magnetic field | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 1.5.03.02.00 | Earth tides | E | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.04.00 | Alpha recoil enhances dissolution | E | NA | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.05.00 | Glass cracking and surface area | E | NA | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.06.00 | Glass recrystallization | E | NA | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.08.00 | Pyrophoricity | E | **S** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.09.00 | Void space (in glass container) | E | NA | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.10.00 | Cellulosic degradation | E | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.13.00 | General corrosion of cladding | E | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.14.00 | Microbial corrosion (MIC) of cladding | E | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.19.00 | Creep rupture of cladding | E | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.20.00 | Pressurization from He production causes cladding failure | E | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.09.00 | Copper corrosion | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.04.03.00 | Erosion or dissolution of backfill | E | NA | **TBD** | **S** | **S** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.04.06.00 | Properties of bentonite | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.04.07.00 | Buffer characteristics | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.05.02.00 | Groundwater flow and radionuclide transport in seals | E | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 2.1.06.04.00 | Flow through the liner | E | NA | NA | NA | **S** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.07.03.00 | Movement of containers | E | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.07.04.00 | Hydrostatic pressure on container | E | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.07.05.00 | Creeping of metallic materials in the EBS | E | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.09.00 | Saturated groundwater flow in waste and EBS | E | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.10.00 | Desaturation/dewatering of the repository | E | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.03.00 | Volume increase of corrosion products | E | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.07.00 | Reaction kinetics in waste and EBS | E | **U** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.09.00 | Electrochemical effects (electrophoresis, galvanic coupling) in waste and EBS | E | **U** | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.11.00 | Waste-rock contact | E | **S** | NA | **S** | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.21.00 | Suspensions of particles larger than colloids | E | NA | NA | NA | **U** | NA | NA | **TBD** | NA | **TBD** | NA | NA | **U** | NA | NA | NA |
| 2.1.11.03.00 | Exothermic reactions in waste and EBS | E | NA | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.11.05.00 | Differing thermal expansion of repository components | E | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.11.08.00 | Thermal effects: chemical and microbiological changes in the waste and EBS | E | **U** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.11.10.00 | Thermal effects on diffusion (Soret effect) in waste and EBS | E | **S** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.12.01.00 | Gas generation | E | **S** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.12.02.00 | Gas generation (He) from fuel decay | E | **S** | NA | **S** | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.12.03.00 | Gas generation ($H_2$) from metal corrosion | E | **S** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.12.04.00 | Gas generation ($CO_2$, $CH_4$, $H_2S$) from microbial degradation | E | **S** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.12.05.00 | Gas generation from concrete | E | NA | NA | **U** | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.12.06.00 | Gas transport in waste and EBS | E | **S** | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.12.07.00 | Radioactive gases in waste and EBS | E | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.12.08.00 | Gas explosions | E | NA | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.13.03.00 | Mutation | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** | **TBD** |
| 2.1.14.02.00 | Criticality *in situ*, nominal configuration, top breach | E | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** |
| 2.1.14.04.00 | Criticality *in situ*, WP internal structures degrade at same rate as waste form, top breach | E | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 2.1.14.11.00 | Near-field criticality, fissile solution is adsorbed or reduced in invert | E | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** |
| 2.1.14.13.00 | Near-field criticality associated with colloidal deposits | E | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** |
| 2.1.14.14.00 | Out-of-package criticality, fuel/magma mixture | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** |
| 2.2.06.03.00 | Changes in stress (due to seismic or tectonic effects) alter perched water zones | E | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.06.04.00 | Effects of subsidence | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.06.05.00 | Salt creep | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.2.07.07.00 | Perched water develops | E | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.14.00 | Density effects on groundwater flow | E | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | **U** | NA | NA | NA |
| 2.2.08.04.00 | Redissolution of precipitates directs more corrosive fluids to containers | E | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.08.05.00 | Osmotic processes | E | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.08.07.00 | Radionuclide solubility limits in the geosphere | E | NA | NA | NA | **U** | NA | NA | **TBD** | NA | **TBD** | NA | NA | **U** | **U** | **U** | NA |
| 2.2.10.13.00 | Density-driven groundwater flow (thermal) | E | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.11.01.00 | Naturally occurring gases in geosphere | E | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.11.02.00 | Gas pressure effects | E | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.11.03.00 | Gas transport in geosphere | E | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.12.00.00 | Undetected features (in geosphere) | E | NA | NA | NA | NA | **TBD** | **TBD** | NA | **TBD** | **TBD** | NA | NA | **U** | NA | NA | NA |
| 2.2.14.02.00 | Far-field criticality, precipitation in organic reducing zone in or near water table | E | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **S** |
| 2.2.14.03.00 | Far-field criticality, sorption on clay/zeolite in TSbv | E | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **S** |
| 2.2.14.06.00 | Far-field criticality, precipitation in fractures of TSw rock | E | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **U** |
| 2.3.04.01.00 | Surface water transport and mixing | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **U** |
| 2.3.06.00.00 | Marine features | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **S** |
| 2.3.09.01.00 | Animal burrowing/intrusion | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **U** | NA | **S** |
| 2.3.13.03.00 | Effects of repository heat on biosphere | E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 3.3.03.01.00 | Contaminated nonfood products and exposure | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 3.3.06.00.00 | Radiological toxicity /effects | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 3.3.06.01.00 | Toxicity of mined rock | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 3.3.06.02.00 | Sensitization to radiation | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **S** |
| 3.3.07.00.00 | Nonradiological toxicity/effects | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **S** |
| 3.3.08.00.00 | Radon and radon daughter exposure | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** | NA |
| 2.2.07.03.00 | Capillary rise | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** |
| 2.4.08.00.00 | Wild and natural land and water use | E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | **S** |
| 1.4.07.01.00 | Water management activities | E | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | **TBD** | **TBD** | **TBD** | **S** |
| 2.1.02.15.00 | Acid corrosion of cladding from radiolysis | E (?) | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.2.03.03.00 | Seismicity associated with igneous activity | E ? | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 3.2.07.01.00 | Isotopic dilution | E ? | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | **U** |
| 1.1.09.00.00 | Schedule and planning | E* | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** |
| 2.1.09.02.00 | Interaction with corrosion products | E? | NA | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.11.00 | Waterlogged rods | ? | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.06.00 | Episodic/pulse release from repository | ? | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.14.08.00 | Far-field criticality associated with colloidal deposits | ? | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **U** |
| 1.1.02.02.00 | Effects of preclosure ventilation | ?? | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |
| 2.2.14.04.00 | Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ | ?? | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **U** |
| 2.3.02.01.00 | Soil type | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** | **U** | **U** |
| 2.3.02.02.00 | Radionuclide accumulation in soils | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **U** |
| 2.3.02.03.00 | Soil and sediment transport | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** | **U** | **S** |
| 2.3.13.02.00 | Biosphere transport | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** | NA |
| 3.3.04.03.00 | External exposure | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** | NA |
| 2.3.11.01.00 | Precipitation | I/E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **U** | **U** | **S** |
| 2.3.13.01.00 | Biosphere characteristics | I/E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | NA |
| 2.4.01.00.00 | Human characteristics (physiology, metabolism) | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 2.4.03.00.00 | Diet and fluid intake | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 2.4.04.01.00 | Human lifestyle | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | NA |
| 2.4.07.00.00 | Dwellings | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 2.4.09.01.00 | Agricultural land use and irrigation | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | **S** |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 3.3.01.00.00 | Drinking water, foodstuffs and drugs, contaminant concentrations in | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 3.3.02.01.00 | Plant uptake | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 3.3.02.02.00 | Animal uptake | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 3.3.04.01.00 | Ingestion | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA |
| 1.1.07.00.00 | Repository design | I/E | **TBD** | **TBD** | **U** | **U** | NA | **TBD** | NA | NA | NA | **TBD** | NA | NA | NA | NA | **TBD** |
| 1.1.08.00.00 | Quality control | I/E | **TBD** | **TBD** | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** |
| 1.2.02.01.00 | Fractures | I/E | NA | **TBD** | **TBD** | NA | **TBD** | **TBD** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 1.2.02.02.00 | Faulting | I/E | NA | **TBD** | NA | NA | **TBD** | **TBD** | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA |
| 1.3.07.02.00 | Water table rise | I/E | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | **TBD** | **S** |
| 1.4.04.01.00 | Effects of drilling intrusion | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** |
| 1.4.07.02.00 | Wells | I/E | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | **TBD** | NA |
| 2.1.13.02.00 | Radiation damage in waste and EBS | I/E | **S** | **TBD** | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.3.11.02.00 | Surface runoff and flooding | I/E | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **S** |
| 2.3.11.04.00 | Groundwater discharge to surface | I/E | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | **TBD** | **TBD** | **TBD** | **U** |
| 3.2.10.00.00 | Atmospheric transport of contaminants | I/E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | **TBD** | **S** |
| 0.1.02.00.00 | Timescales of concern | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 0.1.03.00.00 | Spatial domain of concern | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 0.1.09.00.00 | Regulatory requirements and exclusions | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** | **S** | **S** | **S** |
| 0.1.10.00.00 | Model and data issues | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 1.1.13.00.00 | Retrievability | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** |
| 1.2.03.01.00 | Seismic activity | I | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 1.2.04.01.00 | Igneous activity | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | **TBD** | NA |
| 1.2.04.02.00 | Igneous activity causes changes to rock properties | I | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA |
| 1.2.04.05.00 | Magmatic transport of waste | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA |
| 1.2.04.06.00 | Basaltic cinder cone erupts through the repository | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | **S** |
| 1.2.10.02.00 | Hydrologic response to igneous activity | I | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA |
| 1.3.01.00.00 | Climate change, global | I | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | **U** | **U** | **U** | NA |
| 1.4.02.02.00 | Inadvertent human intrusion | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 1.4.04.00.00 | Drilling activities (human intrusion) | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 2.1.01.01.00 | Waste inventory | I | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | **TBD** | **TBD** | **S** |
| 2.1.01.02.00 | Codisposal/colocation of waste | I | **TBD** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.01.03.00 | Heterogeneity of waste forms | I | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.02.01.00 | DSNF degradation, alteration, and dissolution | I | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.02.02.00 | CSNF alteration, dissolution, and radionuclide release | I | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.02.03.00 | Glass degradation, alteration, and dissolution | I | NA | NA | **TBD** | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.07.00 | Gap and grain release of Cs, I | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** |
| 2.1.02.16.00 | Localized corrosion (pitting) of cladding | I | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.17.00 | Localized corrosion (crevice corrosion) of cladding | I | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.18.00 | High dissolved silica content of waters enhances corrosion of cladding | I | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.21.00 | Stress corrosion cracking (SCC) of cladding | I | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.22.00 | Hydride embrittlement of cladding | I | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.23.00 | Cladding unzipping | I | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.24.00 | Mechanical failure of cladding | I | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.25.00 | DSNF cladding degradation | I | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.01.00 | Corrosion of waste containers | I | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.02.00 | Stress corrosion cracking of waste containers | I | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.03.00 | Pitting of waste containers | I | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.04.00 | Hydride cracking of waste containers | I | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.05.00 | Microbially-mediated corrosion of waste container | I | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.06.00 | Internal corrosion of waste container | I | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.07.00 | Mechanical impact on waste container | I | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.08.00 | Juvenile and early failure of waste containers | I | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.10.00 | Container healing | I | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.03.11.00 | Container form | I | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |
| 2.1.03.12.00 | Container failure (long-term) | I | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |
| 2.1.04.01.00 | Preferential pathways in the backfill | I | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.04.02.00 | Physical and chemical properties of backfill | I | NA | **TBD** | **TBD** | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.04.04.00 | Mechanical effects of backfill | I | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 2.1.04.05.00 | Backfill evolution | I | NA | **TBD** | **TBD** | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.04.08.00 | Diffusion in backfill | I | NA | NA | **S** | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.04.09.00 | Radionuclide transport through backfill | I | NA | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.05.01.00 | Seal physical properties | I | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.05.03.00 | Seal degradation | I | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.06.01.00 | Degradation of cementitious materials in drift | I | NA | **TBD** | **TBD** | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.06.02.00 | Effects of rock reinforcement materials | I | NA | **TBD** | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.06.03.00 | Degradation of the liner | I | NA | **TBD** | **S** | **S** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.06.05.00 | Degradation of invert and pedestal | I | NA | **TBD** | **TBD** | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.06.06.00 | Effects and degradation of drip shield | I | **TBD** | **TBD** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.06.07.00 | Effects at material interfaces | I | **TBD** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.07.01.00 | Rockfall (large block) | I | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.07.02.00 | Mechanical degradation or collapse of drift | I | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |
| 2.1.07.06.00 | Floor buckling | I | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.01.00 | Increased unsaturated water flux at the repository | I | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.02.00 | Enhanced influx (Philip's drip) | I | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.03.00 | Repository dry-out due to waste heat | I | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.08.04.00 | Condensation forms on backs of drifts | I | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.05.00 | Flow through invert | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.06.00 | Wicking in waste and EBS | I | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.08.00 | Induced hydrological changes in the waste and EBS | I | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.11.00 | Resaturation of repository | I | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.01.00 | Properties of the potential carrier plume in the waste and EBS | I | NA | NA | **TBD** | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.04.00 | Radionuclide solubility, solubility limits, and speciation in the waste form and EBS | I | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.05.00 | In-drift sorption | I | NA | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.06.00 | Reduction-oxidation potential in waste and EBS | I | **TBD** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.08.00 | Chemical gradients/enhanced diffusion in waste and EBS | I | **U** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 2.1.09.10.00 | Secondary phase effects on dissolved radionuclide concentrations at the waste form | I | NA | NA | **TBD** | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.12.00 | Rind (altered zone) formation in waste, EBS, and adjacent rock | I | NA | **TBD** | **TBD** | **S** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.13.00 | Complexation by organics in waste and EBS | I | NA | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.14.00 | Colloid formation in waste and EBS | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.15.00 | Formation of true colloids in waste and EBS | I | NA | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.16.00 | Formation of pseudo-colloids (natural) in waste and EBS | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.17.00 | Formation of pseudo-colloids (corrosion products) in waste and EBS | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.18.00 | Microbial colloid transport in the waste and EBS | I | NA | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.19.00 | Colloid transport and sorption in the waste and EBS | I | NA | NA | NA | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.09.20.00 | Colloid filtration in the waste and EBS | I | NA | NA | NA | **S** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.11.01.00 | Heat output/temperature in waste and EBS | I | **TBD** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.11.02.00 | Nonuniform heat distribution/edge effects in repository | I | NA | NA | **TBD** | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.11.04.00 | Temperature effects/coupled processes in waste and EBS | I | **S** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.11.06.00 | Thermal sensitization of waste containers increases fragility | I | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.11.07.00 | Thermally induced stress changes in waste and EBS | I | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **U** |
| 2.1.11.09.00 | Thermal effects on liquid or two-phase fluid flow in the waste and EBS | I | **S** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.13.01.00 | Radiolysis | I | **U** | NA | **TBD** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.14.01.00 | Criticality in waste and EBS | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.14.03.00 | Criticality *in situ*, WP internal structures degrade faster than waste form, top breach | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.14.05.00 | Criticality *in situ*, WP internal structures degrade slower than waste form, top breach | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.14.06.00 | Criticality *in situ*, waste form degrades in place and swells, top breach | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.14.07.00 | Criticality *in situ*, bottom breach allows flow through WP, fissile material collects at bottom of WP | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 2.1.14.08.00 | Criticality *in situ*, bottom breach allows flow through WP, waste form degrades in place | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.14.09.00 | Near-field criticality, fissile material deposited in near-field pond | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.14.10.00 | Near-field criticality, fissile solution flows into drift lowpoint | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.1.14.12.00 | Near-field criticality, filtered slurry or colloidal stream collects on invert surface | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.2.01.01.00 | Excavation and construction-related changes in the adjacent host rock | I | NA | **TBD** | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.01.02.00 | Thermal and other waste and EBS-related changes in the adjacent host rock | I | NA | **TBD** | **TBD** | **TBD** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.01.03.00 | Changes in fluid saturations in the excavation disturbed zone | I | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.01.04.00 | Elemental solubility in excavation disturbed zone | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.01.05.00 | Radionuclide transport in excavation disturbed zone | I | NA | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **S** |
| 2.2.03.01.00 | Stratigraphy | I | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA |
| 2.2.03.02.00 | Rock properties of host rock and other units | I | NA | **TBD** | NA | NA | **TBD** | **TBD** | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.06.01.00 | Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock | I | NA | NA | NA | NA | **TBD** | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA |
| 2.2.06.02.00 | Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults | I | NA | NA | NA | NA | **TBD** | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.01.00 | Locally saturated flow at bedrock/alluvium contact | I | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.02.00 | Unsaturated groundwater flow in geosphere | I | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.04.00 | Focusing of unsaturated flow (fingers, weeps) | I | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.05.00 | Flow and transport in the UZ from episodic infiltration | I | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.08.00 | Fracture flow in the unsaturated zone | I | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.09.00 | Matrix imbibition in the unsaturated zone | I | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.10.00 | Condensation zone forms around drifts | I | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.07.11.00 | Return flow from condensation cap/resaturation of dry-out zone | I | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 2.2.07.12.00 | Saturated groundwater flow | I | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | **TBD** | NA |
| 2.2.07.13.00 | Water-conducting features in the saturated zone | I | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | NA | NA |
| 2.2.07.15.00 | Advection and dispersion | I | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.07.16.00 | Dilution of radionuclides in groundwater | I | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | **TBD** | NA | **TBD** | NA |
| 2.2.07.17.00 | Diffusion in the saturated zone | I | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | **TBD?** | NA | NA | NA |
| 2.2.08.01.00 | Groundwater chemistry/composition in UZ and SZ | I | NA | NA | **TBD** | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | **TBD** | NA |
| 2.2.08.02.00 | Radionuclide transport occurs in a carrier plume in geosphere | I | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.08.03.00 | Geochemical interactions in geosphere (dissolution, precipitation, weathering) and effects on radionuclide transport | I | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.08.06.00 | Complexation in geosphere | I | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA |
| 2.2.08.08.00 | Matrix diffusion in geosphere | I | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.08.09.00 | Sorption in UZ and SZ | I | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | **TBD** | **S** |
| 2.2.08.10.00 | Colloidal transport in geosphere | I | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | **TBD** | NA | NA | **S** |
| 2.2.08.11.00 | Distribution and release of nuclides from the geosphere | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | **S** |
| 2.2.09.01.00 | Microbial activity in geosphere | I | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **S** |
| 2.2.10.01.00 | Repository-induced thermal effects in geosphere | I | NA | NA | **TBD** | NA | **TBD** | **TBD** | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.10.02.00 | Thermal convection cell develops in SZ | I | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.10.03.00 | Natural geothermal effects | I | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.10.04.00 | Thermo-mechanical alteration of fractures near repository | I | NA | **TBD** | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.10.05.00 | Thermo-mechanical alteration of rocks above and below the repository | I | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.10.06.00 | Thermo-chemical alteration (solubility, speciation, phase changes, precipitation/dissolution) | I | NA | NA | **TBD** | NA | NA | **TBD** | **TBD** | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.10.07.00 | Thermo-chemical alteration of the Calico Hills unit | I | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.10.08.00 | Thermo-chemical alteration of the saturated zone | I | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA |
| 2.2.10.09.00 | Thermo-chemical alteration of the Topopah Spring basal vitrophyre | I | NA | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.10.10.00 | Two-phase bouyant flow/heat pipes | I | NA | NA | **TBD** | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |

**Table 5. FEP screening argument evaluation (NA = Not Applicable, S = Satisfactory, U = Unsatisfactory, TBD = To Be Determined) (cont'd)**

| Primary FEP # | FEP Description | Include = I Exclude = E | Integrated Subissues | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ENG1 | ENG2 | ENG3 | ENG4 | UZ1 | UZ2 | UZ3 | SZ1 | SZ2 | Direct1 | Direct2 | Dose1 | Dose2 | Dose3 | TSPA |
| 2.2.10.11.00 | Natural air flow in unsaturated zone | I | NA | NA | NA | NA | **TBD** | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.10.12.00 | Geosphere dry-out due to waste heat | I | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.2.14.01.00 | Critical assembly forms away from repository | I | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **S** |
| 2.2.14.05.00 | Far-field criticality, precipitation in perched water above TSbv | I | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **S** |
| 2.2.14.07.00 | Far-field criticality, dryout produces fissile salt in a perched water basin | I | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **S** |
| 2.3.01.00.00 | Topography and morphology | I | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | **TBD** | NA | NA | **TBD** | NA | **S** |
| 2.3.11.03.00 | Infiltration and recharge (hydrologic and chemical effects) | I | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | **S** |
| 2.4.09.02.00 | Animal farms and fisheries | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** | NA | **S** | **S** |
| 2.4.10.00.00 | Urban and industrial land and water use | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **TBD** | **S** |
| 3.1.01.01.00 | Radioactive decay and ingrowth | I | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | **TBD** | **S** |
| 3.3.02.03.00 | Bioaccumulation | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** | NA |
| 3.3.05.01.00 | Radiation doses | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** | NA |
| 3.3.04.02.00 | Inhalation | I | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **S** | NA |
| 1.2.04.04.00 | Magma interacts with waste | I (in VA) | **TBD** | **TBD** | NA | **TBD** | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |
| 1.2.04.07.00 | Ashfall | I (in VA) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | **TBD** | **TBD** | **S** |
| 1.2.04.03.00 | Igneous intrusion into repository | I ? | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | **TBD** | NA | NA | NA | NA | NA |
| 2.1.10.01.00 | Biological activity in waste and EBS | I ? | **U** | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.02.12.00 | Cladding degradation before YMP receives it | I* | NA | NA | **TBD** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 2.1.08.07.00 | Pathways for unsaturated flow and transport in the waste and EBS | I? | NA | NA | **U** | **U** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

**AC** ***The LA contains a comprehensive list of FEPs that are present or might occur in the Yucca Mountain region (YMR) consistent with the site characterization data and includes those FEPs that have the potential to influence repository performance. Moreover, the comprehensive FEPs list includes, but is not limited to, potentially disruptive events related to igneous activity (IA) (extrusive and intrusive), seismic shaking (high frequency, low magnitude and rare large magnitude events), tectonic evolution (slip on existing faults and formation of new faults), climatic change (change to pluvial conditions), and criticality.***

STAFF REVIEW:

Staff found the methodology explained in the Engineered Barrier System Features, Events, and Processes and Degradation Modes Analysis document (CRWMS M&O, 2000c) acceptable. The methodology is aimed at the identification of FEPs related to degradation of the EBS. By means of an approach that combines the use of schematics of the EBS, logic diagrams, and fault tree diagrams, FEPs pertaining to the EBS have been identified, including common-mode failures. A table summarizing new FEPs (i.e., not described in the FEP database) is available in the report. Staff considers this approach adequate, for demonstrating comprehensiveness of the FEP database. No other examples of similar approaches are yet available. The approach used to construct the list of FEPs should be fully documented to demonstrate comprehensiveness.

Areas of deficiency are:

<u>Lack of Documentation on the Construction of the FEP Database</u>

— In several FEP AMRs (e.g., CRWMS M&O, 2000b, p. 5), it is stated that additional FEPs were identified by a variety of methods, including expert judgment, informal elicitation, event tree analysis, stakeholder review, and regulatory stipulation. However, there is no documentation of the construction of the FEP Database, and staff could not evaluate the adequacy of the approach.

<u>Insufficient Assurance that the FEP List Is Consistent With Site Characterization Data</u>

— None of the FEPs AMRs reviewed to date provides an adequate basis to evaluate whether all FEPs consistent with the YM site characterization data are included. Documentation pertaining to this FEPs evaluation is scant in the FEPs AMRs and is usually limited to a brief overview of the origins of the database (e.g., CRWMS M&O, 2000d).

— Although it is very difficult to ensure that all FEPs are identified and listed, DOE needs to provide reasonable assurance that the initial FEP list was derived, among other things, from site characterization studies.

Missing FEPs

— Particular examples of missing FEPs have been selected to demonstrate this area of deficiency. The examples do not constitute a comprehensive list, and additional examples may be available in other IRSRs.

  – Because criticality changes the radionuclide inventory, adequate consideration should be given to the transport of shorter half-life radionuclides. The inventory utilized in performance assessment calculations was developed without consideration of changes to the initial inventory resulting from criticality.

  – The following scenario is not explicitly addressed in the YMP FEP Database: an *in situ* criticality event resulting from a concurrent top and bottom breach where the neutron absorber degrades faster than the fuel. The neutron absorber is flushed from the WP followed by fuel degradation. The fuel accumulates at the bottom of the WP and plugs the breach such that moderating water can collect within the WP. An alternative to the above scenario could result if the neutron absorber degraded more slowly than the fuel. The neutron absorber would remain in the design location, thereby becoming less effective at preventing a criticality event for the fuel deposited at the bottom of the WP.

  – There appears to be no consideration of the galvanic interaction between cladding and spent nuclear fuel.

  – If the WP is to be assembled with a gap between the inner and outer container to release any thermal stress caused by differing thermal expansion coefficients, the consequences of such design should be considered, such as shock-caused seismicity or corrosion products accumulated in such a gap.

  – Coupled processes must be included in the analysis. For example, it is necessary to consider the effect of rockfall on drip shields and waste packages that are partially corroded. This type of FEP would reduce the ability of a partially failed engineered barrier to prevent water contact. It is not evident that such a FEP has been considered.

STATUS:

Open. Missing FEPs have been identified and there is lack of documentation on the construction approach of the YMP FEP Database. DOE needs to provide further documentation of the approach to constructing the FEP Database and justification of its comprehensiveness.

DOE also needs to assure that all site characterization data, as well as engineering design parameters, are incorporated into the FEP Database.

The adoption of a systematic approach for the identification of new FEPs, such as the one described in the Engineered Barrier System Features, Events, and Processes and Degradation Modes Analysis document (CRWMS M&O, 2000c), would help enhance staff confidence that the YMP FEP Database is comprehensive.

**AC** ***The classification of the initial FEP list into categories of FEPs is comprehensive, clearly documented, and technically complete. The FEP categories are representative of the individual FEPs in a category*.**

STAFF REVIEW:

DOE has classified FEPs as primary and secondary, with preliminary classification results reported in the draft YMP FEP database. However, the objective of most of the reviewed FEP AMRs is to develop screening arguments for primary FEPs, disregarding the classification process. There is no explicit mention of the secondary FEPs enclosed by each primary category, with the exception of the UZ FEP AMR (CRWMS M&O, 2000g). In general, limited attention is given to documentation of the classification process in the reviewed DOE documents.

<u>Unclear/Missing Documentation</u>

— There is insufficient assurance that primary FEPs envelop all secondary FEPs. Documentation pertaining to the categorization decisions is limited to generic statements in all FEP AMRs reviewed. These generic statements assure that the secondary FEPs "can be aggregated into a single primary FEP" (CRWMS M&O, 2000d), or that "the secondary FEPs are a subset of the primary FEPs" (CRWMS M&O, 2000a). Categorization is an essential component of the scenario analysis, because screening arguments are developed for primary FEPs only. The reviewed documents did not offer any specific, FEP-by-FEP arguments to justify that the FEPs have been properly categorized.

— There is insufficient assurance that secondary FEPs of an "included" primary FEP are indeed incorporated into the TSPA analysis. Documentation pertaining to model abstraction of secondary FEPs is limited to generic statements in all FEP AMRs reviewed. For example, DOE assures that "disposition of the primary FEPs … are sufficient to address secondary FEPs" (CRWMS M&O, 2000e). Specific FEP-by-FEP documentation is necessary to provide assurance that categorization is appropriate in light of possible future incorporation into a model abstraction.

<u>Incomplete or Inappropriate Categorization</u>

— Several primary FEPs are excluded in Revision 00b of the YMP FEP database that contain secondary FEPs that are included in the TSPA disposition. Examples are

| | |
|---|---|
| *2.3.02.01.00* | *Soil type* |
| *2.3.11.04.00* | *Groundwater discharge to surface* |
| *1.3.07.01.00* | *Drought/water table decline* |

*2.1.14.02.00* *Criticality in situ, nominal configuration, top breach*
*2.1.14.04.00* *Criticality in situ, WP internal structures degrade at same rate as waste form, top breach*

Staff considers that the preceding problem (excluding the primary FEP despite the inclusion of secondary FEPs) could be the result of inappropriate categorization. Secondary FEPs may be included that should be considered primary. Staff also acknowledges the preliminary nature of the YMP FEP Database, Revision 00b. Nonetheless, it is desirable that later revisions of the YMP FEP database address this consistency issue.

— *Biosphere characteristics (FEP 2.3.13.01.00)* includes a secondary FEP for *Plants (FEP 2.3.13.01.07)* but not one for animals (CRWMS M&O, 2000d). *Biosphere transport (FEP 2.3.13.02.00)* contains only two secondary FEPs related to surface water, gas, and biogeochemical transport processes. Other potential biosphere transport processes are not included as secondary FEPs (e.g., resuspension of soils), suggesting incomplete identification of secondary FEPs.

— *Animal farms and fisheries (FEP 2.4.09.02.00)* includes secondary FEPs such as *Ranching (FEP 2.4.09.02.02)* and *Fish farming (FEP 2.4.09.02.01)*. Likewise, farm types also relate to *Agricultural land use and irrigation (FEP 2.4.09.01.00)* but do not appear as secondary FEPs under this primary FEP (CRWMS M&O, 2000d).

STATUS:

Open. DOE needs to provide sufficient documentation to demonstrate the adequacy of the classification of FEPs into categories. The scope of the FEP AMRs could be increased to include documentation on the classification process. Alternatively, additional documentation addressing the issue of the FEP classification could be produced. Explanation of the classification process is important for the verification to ensure that all secondary FEPs are included under primary FEPs and that the screening arguments for primary FEPs are also valid for secondary FEPs. Although the few examples of inadequate classification are greatly outnumbered by satisfactory FEP classification, the examples presented represent potential situations where processes could be overlooked. Care should be taken in maintaining details pertaining to model abstraction of included primary FEPs. In particular, details discussed in secondary FEPs should be properly incorporated in the TSPA disposition.

**AC** ***FEPs that are excluded from the PA for the YM repository are identified and sufficient technical basis is provided for the exclusion. Specifically:***

- ***FEPs that are not applicable to the YM repository for reasons associated with, but not limited to, repository design or site and regional characteristics are identified and sufficient justification is provided.***

STAFF REVIEW:

DOE does not use this subcriterion as a screening argument. DOE has adopted only two screening arguments—consequence and probability. DOE treats “not credible” or “not applicable” as a variant of the “low probability” screening argument for FEPs (Swift, 2000). Nonetheless, staff has also found examples in which “not credible” or “not applicable” is treated as a variant of “low consequence.” For example, *Copper corrosion (FEP 2.1.03.09.00)* is excluded on the basis of low consequence (CRWMS M&O, 1999b). The rationale for the screening is that copper will not be employed in the EBS construction, and thus this FEP has no relevance to YM. Examples where FEPs are excluded on the basis of zero probability are available in the EBS FEP AMR (CRWMS M&O, 2000b): FEPs *2.1.04.06.00, 2.1.04.07.00, 2.1.06.03.00, 2.1.06.04.00*, and *2.1.07.04.00*. Zero probability has been assigned to these FEPs because they are associated with design elements not available in EDA-II, or because they are related to repositories built in the saturated zone.

STATUS:

Closed. However, for the sake of clarity staff suggests consistency in treating FEPs with zero probability. For example, exclusion of *Copper corrosion (FEP 2.1.03.09.00)* on the basis of “low consequence” could imply that copper is used in the repository, but its corrosion has no effect on the repository performance. Excluding copper corrosion on the basis of zero probability as proposed by Swift (2000) seems more appropriate instead of low consequence.

- ***Events that are screened from the PA on the basis that their probability falls below the regulatory criterion are identified and sufficient justification is provided.***

STAFF REVIEW

Staff expects to review quantitative and well documented arguments when probability is used as screening criterion. Such screening arguments should include, but not be limited to, the value of the probability derived for the considered FEP. In general, such quantitative arguments, and often the final derived probability, are missing from screening arguments. Examples of deficient screening arguments are listed below:

— *Seismic activity (FEP 1.2.03.01.00)* (CRWMS M&O, 2000g) is excluded based on low consequence and low probability. No quantitative argument is provided that supports the less-than-threshold probability ($10^{-8}$) for the formation of new faults or enhancement of small faults.

— *Hydrological response to seismic activity (FEP 1.2.10.01.00)* (CRWMS M&O, 2000g) is screened out based on low consequence and low probability. However, the detailed argument does not include quantitative support (e.g., back-of-the-envelope calculations) only a list of observations and qualitative statements is presented to support the conclusion that “the migration of the large hydraulic gradient” does not need to be considered.

STATUS:

Open. Low probability arguments for screening need to be supported by estimates of probabilities and that the probability is below the regulatory threshold.

- ***FEPs related to the geologic setting or the degradation, deterioration, or alteration of EBs (including those processes that would affect the performance of natural barriers) that are screened from the PA on the basis that their omission would not significantly change the magnitude and time of the average annual dose during regulatory period, are identified and sufficient justification is provided.***

STAFF REVIEW:

Staff reviewed FEP AMRs, and several deficiencies were identified related to the use of preliminary, incomplete, and uncertain information, and incomplete screening arguments. Particular examples are discussed below.

<u>Use of preliminary and uncertain information to screen FEPs</u>

— In CRWMS M&O (2000f), it is assumed that thermal effects inhibit contaminant transport from the UZ to the SZ and will not have a significant negative consequence. This assumption is used to screen out FEPs *2.2.10.02.00* (p. 37), *2.2.10.01.00*, *2.2.10.13.00*, *2.2.10.07.00*, and *2.2.10.08.00* (p. 44). However, there is limited information to support this assumption, and further verification is required (CRWMS M&O, 2000f, p. 20). Thus, the technical basis to screen these FEPs is severely limited.

— Staff found frequent use of the argument “exclude-to be verified (TBV) pending additional data and/or analysis.” Examples of FEPs screened out with preliminary information are FEPs *1.2.03.02.00*, *2.1.03.04.00*, *2.1.03.05.00*, *2.1.03.06.00*, and *2.1.13.02.00* (CRWMS M&O, 1999b). Staff is concerned that by screening out FEPs based on preliminary information, the TSPA modeling effort may be incomplete. Further studies may indicate that the screened out FEPs are relevant, or further studies may provide insufficient information to support the screening. Effort must be aimed at completing the needed studies to identify all relevant FEPs to be included in the TSPA modeling effort.

— In CRWMS M&O (2000g), FEP *1.2.02.01.00* is screened as “excluded” on the basis of low consequence for the effects of changes to the fracture system. No numerical evidence is provided for this screening decision. The screening argument provides reference to a sensitivity study, but only in connection to fracture aperture. The remaining argument is based on a to-be-verified assumption, listed as assumption No. 15 in this document. The validity of this assumption is unclear.

Incomplete screening arguments

— The DOE utilizes the WAPDEG code to estimate the number of WPs that have failed (i.e., the number of WP that have suffered first-patch penetration) and also the number of penetration openings versus time for a single WP (i.e., the extent of the WP damage). The extent of the WP damage and the water dripping flux on the WPs are used to compute the rate of radionuclide release. Therefore, in the DOE approach, the extent of the WP damage is correlated to the rate of radionuclide release. The DOE does have a diffusive component to their release model which is not dependent on the advective dripping flux. Staff found that the following screening arguments are incomplete.

  – For *internal corrosion of waste container (FEP 2.1.03.06.00)* the screening argument proposes that the existence of an inert environment inside the WP renders this corrosion mechanism irrelevant (CRWMS M&O, 1999b, p. 23). However, after penetration of the WP, water could be available in its interior. Under this circumstance, corrosion from the inside-out, probably enhanced by radiolysis, cannot be neglected. With respect to the DOE approach, it is relevant to track the extent of WP damage, so that the rate of radionuclide release can be estimated. Therefore, this FEP should be further evaluated.

  – *Mechanical impact on waste container and drip shield (FEP 2.1.03.07.00)* includes Damage by swelling corrosion products (CRWMS M&O, 1999b, p. 24). This particular secondary FEP (mechanical effect by swelling corrosion products) has been screened out based on the fact that corrosion products of the outer container are not confined to a tight space. This rationale applies only to the case in which the WP has not been penetrated. A confined space exists between the inner and outer container (see *FEP 2.1.03.02.00*, where it is mentioned that a gap between the outer barrier and the inner barrier will help in releasing any stress by differing thermal expansion coefficients, p. 19). This tightly confined space is available after the outer WP is breached. Under this circumstance, corrosion products from the inner container and accumulated in the gap may induce stress on both containers (inner and outer). Because the DOE computations correlate the extent of the damage to the WP to the rate of radionuclide release, this case cannot be disregarded.

Insufficient and inadequate technical basis for screening

— In CRWMS M&O (2000g), *Episodic Infiltration (FEP 2.2.07.05.00)* is screened as “excluded” on the basis of low consequence. Experimental evidence pointing to the existence of such infiltration is dismissed based on the argument that “models indicate that … a flow transient is negligible with respect to repository performance.” A demonstration that episodic infiltration is insignificant with respect to performance would be required for this line of argumentation. In addition, the representation of episodic infiltration in the models would need to be presented.

— FEPs related to human influence on climate in CRWMS M&O (2000g) have been screened out on the basis of low consequence. The arguments are also not convincing. The summary offered refers to natural, cyclical changes that are presumed to have a stronger influence than that resulting from human activities (assumption 5 in CRWMS M&O, 2000g). No arguments are offered on the validity of this assumption. Thus, the screening argument is not sufficient.

— Examples of biosphere and criticality related primary FEPs in the YMP FEP database with insufficient information in the screening argument are as follows:

Biosphere

| | |
|---|---|
| *2.3.02.01.00* | *Soil type* |
| *2.3.11.04.00* | *Groundwater discharge to surface* |

Criticality

| | |
|---|---|
| *2.1.14.02.00* | *Criticality in situ, nominal configuration, top breach* |
| *2.1.14.04.00* | *Criticality in situ, WP internal structures degrade at same rate as waste form, top breach* |
| *2.1.14.11.00* | *Near-field criticality, fissile solution is adsorbed or reduced in invert* |
| *2.1.14.13.00* | *Near-field criticality associated with colloidal deposits* |
| *2.1.14.14.00* | *Out-of-package criticality, fuel/magma mixture* |
| *2.2.14.06.00* | *Far-field criticality, precipitation in fractures of TSw rock* |

Staff recognizes the preliminary nature of the YMP FEP database. Nonetheless, it is desirable that the technical basis be provided for the screening of these FEPs.

STATUS:

Open. Some deficiencies have been identified that must be addressed with the use of further information, complete screening analyses, and better technical bases for the screening arguments. DOE needs to improve the technical basis for the screening arguments in future releases of the YMP FEP database.

**AC** ***Scenario classes are mutually exclusive and complete, clearly documented, and technically acceptable.***

STAFF REVIEW:

Several AMRs indicate that all included FEPs are combined into scenarios and are represented in the DOE TSPA. For example, in the Disruptive Events FEPs AMR (CRWMS M&O, 2000e, p.13), it is stated that all FEPs expected to occur in the compliance period are combined in a nominal scenario, and all FEPs occurring with a probability less than 1 are combined in disruptive scenarios. Therefore, the staff observes that there is no apparent intent to conduct scenario screening. This DOE/NRC observation by the staff has been corroborated by Swift (2000) in his presentation at the TSPA Technical Exchange on June 6–7, 2000.

Scenario and scenario formation discussed in the TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a) are unclear. For example, in Section 1.4 of the previously cited report (p. 1-14) scenarios are referred to as possible future states of the repository, and the need for screening scenarios is mentioned. On p. 2-7, a scenario is referred to as "a set of similar futures that share common FEPs." On p. 2-8, all included FEPs are described as either to be expected (probability of one) and thus to be part of the nominal scenario, or to have some probability less than one, which classifies them as disruptive FEPs. Figure 2.2-3 in this same document indicates what DOE refers to as scenarios—the combination of the nominal scenario with any or all possible combinations of disruptive scenarios. DOE should clarify the precise meaning of scenario and make a distinction between a scenario (as a sum total of included FEPs) and a specific TSPA realization (which may combine the nominal and one or several disruptive scenarios).

STATUS:

Open. Although generally satisfied, staff is concerned that DOE has not proposed a clear and precise definition of scenario and used such a definition in its documents.

**AC** ***Screening of scenario classes is comprehensive, clearly documented, and technically acceptable. Specifically:***

- ***Scenario classes that are not applicable for a YM repository for reasons such as but not limited to waste characteristics, repository design, or site characteristics—individually or in combination—are identified and sufficient justification is provided for these conclusions.***

STAFF REVIEW:

None of the documents reviewed discusses the screening of any particular scenario. However, in the Disruptive Events FEPs AMR (CRWMS M&O, 2000e, p. 2-8) it is suggested that scenarios could be screened if their combined probability of occurrence is below regulatory threshold. DOE identifies the combination of several disruptive scenarios with the nominal scenario as an "overall" scenario (this identification is confusing because of the use of the same word "scenario" for different definitions). Such a scenario would be screened out if the combined disruptive "subscenarios" had a probability of less than 1 in 10,000. Because only one disruptive scenario has been identified (Swift, 2000), the comment in CRWMS M&O (1999a, p. 1-14) that "the essentially infinite combinations" cannot all be analyzed is inappropriate. In principle, all possible combinations can be modeled because there are only two scenarios to consider.

STATUS:

Closed. Swift (2000) has corroborated at the DOE/NRC TSPA Technical Exchange on June 6–7, 2000, that the two possible scenarios (nominal and disruptive) will be included as part of the TSPA models. Staff believes the methodology is being implemented properly.

- ***Scenario classes that are screened from the PA on the basis that their probability falls below the regulatory criterion are identified and sufficient justification is provided.***

  STAFF REVIEW:

  This screening criterion has not been used by DOE to screen scenarios. Two scenarios have been defined by DOE that will be part of the TSPA model (Swift, 2000).

  STATUS:

  Not applicable.

- ***Scenario classes that are screened from the PA on the basis that their omission would not significantly change the magnitude and time of the average annual dose are identified and sufficient justification is provided.***

  STAFF REVIEW:

  This screening criterion has not been used by DOE to screen scenarios. Two scenarios have been defined by DOE that will be part of the TSPA model (Swift, 2000).

  STATUS:

  Not applicable.

**Transparency and Traceability**

This section discusses issues related to transparency and traceability. Particular emphasis has been placed on the integration and consistency of information among the several DOE documents reviewed in this report. This section also discusses transparency and traceability of the YMP FEP database. Staff acknowledges the preliminary nature of this database. Nonetheless, early feedback on its revision will ensure the improvement of the information of future revisions of the YMP database.

STAFF REVIEW:

To enhance traceability, the DOE has classified FEPs in a database following a numerical nomenclature of the kind x.x.xx.xx.xx, where each digit defines layer, category, heading, and primary and secondary entries. Details of the numeric nomenclature are described, for example, in Table 2 of the Disruptive Events FEPs AMR (CRWMS M&O, 2000e). Description of the FEPs are provided in the FEP AMRs, and references pertinent to the screening argument are given.

PMRs address particular sets of FEPs. It is expected that all PMRs will address the entire set of FEPs. To enhance transparency and traceability, staff recommends the development of a document mapping FEPs to the PMRs. Currently the reviewed PMRs include a table of the included FEPs. These tables could facilitate the review process by specifying the chapter in which each FEP is treated, because in many circumstances, it is not evident how the FEPs are treated.

For example, staff assumes that *Effects of materials interfaces (FEP 2.1.06.07.00)* is developed as part of the crevice corrosion analysis in the *Waste Package Degradation* PMR (CRWMS M&O, 2000h), but the relationship is not explicitly stated in this PMR.

DOE needs to provide a transparent and traceable description of how revision to the FEP database are propagated into AMR's and PMR's, and vice versa. The following areas of concern (resulting from the revision process) have been identified:

<u>Treatment of FEPs by nontopical-related AMRs</u>

> *Waste-rock contact (FEP 2.1.09.11.00)* is "excluded" in CRWMS M&O (2000b) on the basis of "low consequence." However, in the screening argument, it is evident that this FEP is excluded because it falls outside the scope of the AMR. This kind of argument is unacceptable, in that it does not rely on detailed screening arguments.

<u>Inconsistent screening decisions in multiple AMRs</u>

> Some FEPs are treated in multiple FEP AMRs, and, in some cases, screening decisions depend on all the available information in the related FEP AMRs. Examples are given as follows.
>
> — *Container healing (FEP 2.1.03.10.00)* is classified as "included" in CRWMS M&O (2000b) but as "excluded" in CRWMS M&O (1999b). If container healing is excluded in the latter document then it cannot be included in the former document. The general scheme or protocol should help in determining the most general conclusion ("exclude" in the present example).
>
> — *Climate change, global (FEP 1.3.01.00.00)* is screened as "excluded" in CRWMS M&O (2000d), but as "included" in CRWMS M&O (2000g). Secondary FEPs *2.3.11.01.01* through *2.3.11.01.04* of the primary FEP *Precipitation (FEP 2.3.11.01.00)* are screened as "excluded" in CRWMS M&O (2000d), but as "included" in CRWMS M&O (2000g). In both cases, the implication of the screening decision for an AMR must be taken into consideration when elaborating a screening argument for an independent AMR.
>
> Staff is aware that the same FEP can have independent screening decisions when analyzed under different criteria (i.e., they can be both "included" and "excluded" when analyzed in different AMRs). Nonetheless, for the sake of transparency, it is necessary that analysts consider at a higher level (e.g., TSPA or any FEP database) all available information for a particular FEP to arrive at a consistent general screening decision.

<u>Potential for inappropriate transfer of information between DOE documents</u>

> A clear outline of the procedure that will be adopted to ensure traceability of information among the database, AMRs, PMRs, and the TSPA document is not established.
>
> Staff envisions that as new FEPs are discovered or screening arguments are updated, the transfer of information among the database, AMRs, PMRs, and the TSPA model could be

difficult (given the complexity of the analysis) unless an appropriate procedure, scheme, or protocol for the transfer of information is implemented. For example, if a new FEP arises, the protocol must ensure that this FEP is analyzed from the perspective of all PMRs, to ensure that all couplings are taken into account and comprehensive screening arguments are elaborated. Staff envisions that new FEPs will result from new design considerations. For instance, it has been proposed to leave a gap between the inner and outer containers to release or nullify stresses due to differing thermal expansion coefficients [see *FEP 2.1.03.02.00* in CRWMS M&O (1999b, p. 19)]. This gap will have consequences that must be analyzed. For example, during a seismic event, the outer and inner containers could strike each other, raising the stress levels. This new FEP and others related to this design variation must be analyzed from all possible implications that may have effect on repository performance. Screening arguments must be promptly communicated between the AMRs, PMRs, and the YMP database, and an appropriate TSPA disposition must be accomplished. This process could be facilitated with the implementation of a protocol for the transfer of information.

Inconsistencies between FEPs-related information in AMRs and PMRs

In CRWMS M&O (1999b, p. 24) the *Internal corrosion of waste container (FEP 2.1.03.06.00)* is screened as "excluded" on the basis of low consequence. The Waste Package Degradation PMR (CRWMS M&O, 2000h, p. 1-16) repeats this conclusion in Table 1-2. However, in this same PMR (p. 3-99), it is mentioned that corrosion from the inside-out is indeed included in the estimation of the extent of the damage to the WP; thus, it is not true that the *FEP 2.1.03.06.00* has been screened out. This problem could be eliminated by introducing a protocol for information transfer that will ensure consistent treatment of FEPs in the AMRs and PMRs.

Inconsistencies in the YMP FEP database

Information under this subheading corresponds to information contained in the YMP FEP database. Staff acknowledges the preliminary nature of the database. Nonetheless, early revision of its content could guarantee that future revisions of the database address staff concerns.

*Unclear descriptions*

*Dermal sorption (FEP 3.3.04.03.06)* and *Injection (FEP 3.3.04.03.07)* have descriptions that are specific to the WIPP site. The screening arguments are unclear and do not appear to match the FEP name and description. The FEP name, description, screening status and argument for *Intrusion into accumulation zone in the biosphere (FEP 1.4.02.01.12)* appear unrelated and lack sufficient detail to be meaningful.

Some FEP records contain descriptions that are unclear. For example, the description of *Natural ecological development (FEP 2.3.13.01.10)* reads as though it is a rationale for exclusion rather than a description of the topic. The description of *Irradiation (FEP 3.3.04.03.05)* is also written in the style of a rationale for exclusion, noting that "FEPs that relate to human uptake by ingestion, inhalation, irradiation, dermal sorption, and injection have been eliminated from compliance assessment calculations on the basis of low consequence." This statement is inconsistent with TSPA pathways described in the Identification of Ingestion Exposure Parameters AMR (CRWMS M&O, 2000j).

*Lack of screening status*

Examples of primary FEPs without a screening status ("include"/"exclude") are

| | |
|---|---|
| *2.2.14.04.00* | *Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ* |
| *2.2.14.08.00* | *Far-field criticality associated with colloidal deposits* |
| *2.1.13.03.00* | *Mutation* |

*Inconsistencies between screening arguments and TSPA dispositions*

Several FEPs contain discrepancies between the screening argument, presented in the FEP database, and the TSPA disposition. Some examples of FEPs "excluded" in the database screening but "included" in the TSPA disposition are

| | |
|---|---|
| *1.3.07.01.00* | *Drought/water table decline* |
| *2.3.02.02.00* | *Radionuclide accumulation in soils* |
| *3.2.07.01.00* | *Isotopic dilution* |

Some examples of primary FEPs "included" in the database screening but ignored in the TSPA disposition are

| | |
|---|---|
| *2.1.11.07.00* | *Thermally induced stress changes in waste and EBS* |
| *2.3.04.01.00* | *Surface water transport and mixing* |

*Inconsistencies between screening arguments and screening status*

Some FEPs contain contradictions between the screening status and the screening argument. For example, *Natural radionuclide/elements (in host rock disturbed zone) (FEP 3.2.07.01.02)* was "excluded" in the database screening but contained a screening argument that implies it should be "included."

FEPs are screened as "included" in the database but contain screening arguments that imply they should be "excluded." Examples are

| | |
|---|---|
| *1.3.07.01.02* | *Dust storms and desertification* |
| *2.3.11.03.06* | *Surface water chemistry* |

The screening decision to include the secondary-FEP *Precipitation of U below the redox front in the SZ (FEP 2.2.14.04.02)* contradicts the screening argument of the primary-*FEP 2.2.14.04.00* "[Exclude redox front (unlikely) but include evap/precip by hydro-thermal upwell]."

*Inappropriate FEP naming*

Several criticality-related FEPs do not contain "criticality" in the FEP name and are listed below. Adding "criticality" to the FEP name would improve database cataloging and searching.

| | |
|---|---|
| *2.1.14.01.07* | *Nuclear explosions (in waste and EBS)* |
| *2.1.14.03.01* | *Waste package internal structures degrade faster than waste form* |
| *2.1.14.03.02* | *Waste package internal structures collapse* |
| *2.1.14.04.01* | *Waste package internal structures and the waste form degrade at the same rate* |
| *2.1.14.05.01* | *Waste package internal structures degrade slower than waste form* |
| *2.1.14.08.01* | *Neutron absorber system selectively degrades* |
| *2.1.14.08.02* | *Neutron sorbers selectively flushed from containers* |
| *2.1.14.08.03* | *Selective leaching of neutron sorbers* |
| *2.1.14.09.08* | *Pu accumulates in basin pool (in waste and EBS)* |
| *2.1.14.09.09* | *Accumulated 239Pu decays to 235U in basin pool (in waste and EBS)* |
| *2.1.14.10.01* | *Accumulation of clays and sediments in basin (in EBS)* |
| *2.1.14.10.02* | *Differential solubility of neutron poisons* |
| *2.1.14.10.03* | *Selective leaching of fissile materials* |
| *2.1.14.11.01* | *Differential solubility of fissile isotopes* |
| *2.2.14.01.01* | *Reconcentration (release/migration factors) "considered specifically only for the case of criticality"* |
| *2.2.14.01.02* | *Reconcentration (release/migration factors) "considered for one of the criticality scenarios"* |
| *2.2.14.02.01* | *Precipitation of U at reducing zone associated w/organics in alluvial aquifer* |
| *2.2.14.02.02* | *Precipitation of U at reducing zone associated w/organics in Franklin Lake playa* |
| *2.2.14.03.01* | *Accumulation of solute in topographic lows of the altered TSbv* |
| *2.2.14.04.01* | *Precipitation of U in the upwelling zone along some faults* |
| *2.2.14.04.02* | *Precipitation of U below the redox front in the SZ* |

*Lack of appropriate references*

A Criticality PMR is listed in the database for several of the criticality-related FEPs (e.g., FEPs *2.1.14.01.00* to *2.1.14.14.00*, and *2.2.14.01.00* to *2.2.14.08.00*). Staff is not aware that DOE plans to produce a PMR on criticality.

*Multiple screening decisions for the same FEP*

Several FEPs were excluded in one process but included in another. This apparent duplication causes confusion in keeping track of included and excluded FEPs. Staff is aware that a FEP could be “included” as part of a process and “excluded” as part of another. The challenge is to design a database that summarizes all screening decisions and present them in a clear, transparent, and traceable manner.

STATUS:

Open. For sufficient transparency and traceability, DOE needs to improve documentation to achieve completeness and uniqueness. The scheme or protocol for information transfer should permit the update of screening arguments and screening conclusions (“include”/”exclude”) so that analysts share up-to-date and comprehensive information. For example, the removal of the backfill renders some screening arguments invalid and consequently in need of revision. This revision could be facilitated by the implementation of an adequate mechanism for the transfer of information. This scheme or protocol will enhance the consistency of information in the YMP FEP database and the AMRs and PMRs. It will also ensure that all FEPs are provided with complete screening arguments and new FEPs are treated with consistency in all relevant process models.

It is also recommended that tables summarizing the FEPs addressed and the chapter numbers where they are treated be included in PMRs. For the excluded FEPs, DOE should verify that these FEPs are not included as part of the modeling effort. If they are included, then the FEPs should be regarded as "included."

The addition of keywords to FEP entries in the database could facilitate its search. For example, a "criticality" keyword could be added to all the criticality-related FEPs.

A summary of FEPs included in TSPA will improve transparency in scenario analysis by overcoming the confusion associated with the treatment of FEPs that are designated as both "included" and "excluded."

## 5.3 TOTAL SYSTEM PERFORMANCE ASSESSMENT METHODOLOGY: MODEL ABSTRACTION

As discussed in Section 4.3, the methodology of model abstraction has been partitioned into fourteen integrated subissues. The integrated subissues are used in an evaluation of model abstraction methodology to emphasize that a high level of integration is necessary when evaluating a complex process with many components. The ISIs require input from and evaluation by technical staff from various disciplines. The specific disciplines that are involved in the evaluation of an ISI are defined by the KTI subissues linked to a given ISI (See Table 3 of this report). Five generic acceptance criteria (T1 to T5 in the YMRP) have been developed and applied to the methodology of model abstraction, ranging from data suitability to model development and integration of models. Each integrated subissue must satisfy the five generic model abstraction acceptance criteria to be closed prior to a potential LA.

The staff review for issue resolution in model abstraction is based on the following set of questions identified under each review method:

*Data and Model Justification*

- Has DOE demonstrated that sufficient data exist to support the conceptual models and define relevant parameters in DOE's model abstractions?

- Are additional data likely to provide new information that could invalidate prior modeling results and the sensitivity of the performance of the system to the parameter value or model?

- Is the primary source of data appropriately QA qualified (field, laboratory, or natural analog data)?

- Is the definition of parameter values and conceptual models with inadequate data based on other appropriate sources, such as expert elicitation conducted in accordance with NUREG–1563?

- Has DOE performed sensitivity and uncertainty analyses to test for the possible need for additional data?

- Has DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models?

*Data Uncertainty*

- Are the input values used in the model abstractions in TSPA reasonable based on data from the YM region and other applicable laboratory tests and natural analogs?

- Do parameter values, assumed ranges, and probability distributions, reasonably account for uncertainty and variability?

- Are bounding assumptions technically defensible?

- Are the data consistent with the initial and boundary conditions (design features) and the present assumptions of the conceptual models?

- Has correlation between input values been appropriately established in DOE's TSPA?

- How do DOE's input values compare to corresponding input values in the staff data set?

- What is the sensitivity of the system performance to the input values and correlation used by DOE?

*Model Uncertainty*

- Has DOE considered plausible alternative models?

- Has DOE provided supporting information for the conceptual models used in the model abstractions?

- Does the intermediate output of the engineered and natural systems produced by DOE's approach reflect or bound the range of uncertainties owing to alternative modeling approaches?

*Model Support*

- Has DOE demonstrated that the output of the model abstraction reasonably reproduces or bounds the results of the corresponding process-level models or alternative sources of data?

- How does the output of DOE's model abstraction compare to results produced by the detailed process-level model or against field and laboratory data and natural analogs?

*Integration*

- Have consistent and appropriate assumptions and initial and boundary conditions been propagated throughout DOE's abstraction approaches?[7]

- Are the conditions and assumptions used to generate look-up tables or regression equations[8] consistent with all other conditions and assumptions in the TSPA?

- Have important design features that will set the initial and boundary conditions for model abstractions been included?

- Have DOE's dimensionality abstractions[9] appropriately accounted for the various design features, site characteristics, and alternative conceptual approaches?

- Have important physical phenomena and couplings with other model abstractions been included in the TSPA?

- Have DOE's domain-based[10] and temporal-abstractions appropriately handled the physical couplings (T-H-M-C)?

- Has sufficient justification been provided to exclude couplings?

### 5.3.1 Description of the U.S. Department of Energy Approach and U.S. Nuclear Regulatory Commission Staff Evaluation—Model Abstraction

Most of the description and discussion of the U.S. Department of Energy approaches to model abstraction can be found in the appropriate KTI issue resolution status reports. The descriptions that follow for the evaluation of specific model abstractions (Sections 5.3.1.1 through 5.3.1.14) were current as of the VA documentation. Only two IRSRs (CLST and ENFE) for the process KTIs had been updated (Revision 3) to reflect the review of recently received AMRs and PMRs as of the preparation date of this report. Therefore, the next revision of this report will provide an update of NRC's understanding of DOE's approach to model abstraction.

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[7]For TSPA-VA, the types of abstraction are defined in Section 3.3 of the TSPA-VA Plan (TRW Environmental Safety Systems, Inc., 1996).

[8]These regression equations are called response-surface abstractions in the TSPA-VA Plan (TRW Environmental Safety Systems, Inc., 1996).

[9] For example, from three dimensional to two dimensional or one dimensional.

[10]The domain-based concept involves dividing the repository system into a series of sequentially linked spatial domains.

Table 6 provides a summary of the status of resolution for model abstraction (current as of May 15, 2000, therefore it does not reflect any interactions that have taken place after this date). The status table has been updated but, in general, does not reflect review of the AMRs and PMRs, as well as TSPA-SR. Integrated subissue UZ1 (Climate and infiltration) is closed. The remainder of the integrated subissues are currently open. Integrated subissue Dose1 (Dilution of radionuclides in groundwater due to well pumping) was previously identified as being closed because the DOE had not taken any credit for dilution of radionuclide concentrations due to well pumping. However, in the most recent DOE/NRC TSPA Technical Exchange on June 6–7, 2000, the DOE did indicate that the effects of well pumping would be evaluated, therefore, this integrated subissue is open. In addition to providing a summary of the status of resolution for model abstraction, the open KTI subissues were ranked (within an integrated subissue by the appropriate subject matter experts) to identify which areas presented the largest potential impact to an evaluation of risk if the KTI subissue remains unresolved. Smaller numbers are associated with more potential impact.

It is cautioned that closure of all KTI subissues associated with an ISI does not necessarily mean that the ISI is closed. The KTI subissues may not be sufficient to meet the five technical and two programmatic acceptance criteria for each ISI in the YMRP. For example, the Dose3 integrated subissue (Lifestyle of the Critical Group) comprises USFIC1–3, USFIC5, RT3, TSPAI3, and IA2 KTI subissues (see Table 4 and Appendix B). Closure of all these KTI subissues would not close the Dose3 ISI. The status of resolution for each of the KTI subissues that provides input to an ISI is fully documented in the respective KTI IRSRs. In addition, closure of an ISI is possible even if all the associated KTI subissues are not closed. This apparent anomaly results due to the fact that not every item represented by a KTI subissue may be relevant to the associated ISI. For example, KTI subissue SDS3 is open; however, ISI UZ1 is closed. Representation of fractures in the process of climate and infiltration is necessary; however, NRC staff have concluded that the abstraction of fractures and their impact on the processes of climate and infiltration have been appropriately completed and has been documented by the DOE. Greater characterization of fracture networks and their properties are not likely to change the abstraction considered in the UZFT model as a result of the range of data currently in use.

DOE/NRC Technical Exchanges provide a public forum for NRC and DOE to discuss technical issues. Some items of potential concern to closure of the model abstraction subissue were highlighted during the most recent DOE/NRC TSPA Technical Exchange on June 6–7, 2000. These concerns included:

| | | |
|---|---|---|
| Data Uncertainty | — | Selection of which parameters need to be sampled in the PA (or process-level models), |
| | — | Data falling outside the range of the results of a process model, |
| Model Uncertainty | — | Lack of or insufficient technical basis for selection of nonconservative alternative conceptual models, and |
| Integration | — | Calculational integration/averaging (i.e., changing the results of calculations by transferring data between models with different numerical grid sizes. |

**Table 6. Status of resolution in model abstraction**

| Integrated Subissue | Integration | Associated KTI Subissues | Data and Model Sufficiency | Data Uncertainty | Model Uncertainty | Model Support |
|---|---|---|---|---|---|---|
| ENG1 - Degradation of Engineered Barriers | **OPEN** | CLST1 | 1 | 1 | 1 | 1 |
| | | CLST5 | 2 | 2 | 2 | 2 |
| | | ENFE2 | 3 | 3 | 3 | 3 |
| | | TEF1 | 4 | 4 | 4 | 4 |
| | | TEF2 | 5 | 5 | 5 | 5 |
| | | RDTME3 | | | | 6 |
| | | RDTME4 | | | | |
| | | CLST2 | | | | |
| | | CLST6 | | | | |
| ENG2 - Mechanical Disruption of Engineered Barriers | **OPEN** | IA2 | 1 | 1 | 1 | 1 |
| | | CLST1 | 2 | 2 | 2 | 2 |
| | | CLST5 | 3 | 3 | 3 | 3 |
| | | RDTME3 | 4 | 4 | 4 | 4 |
| | | SDS3 | | 5 | 5 | |
| | | SDS4 | 6 | 6 | 6 | 6 |
| | | CLST6 | | | | |
| | | SDS1 | | | | |
| | | SDS2 | | | | |
| | | CLST2 | | | | |
| | | RDTME2 | | | | |
| ENG3 - Quantity and Chemistry of Water Contacting … | **OPEN** | ISI-specific | 1 | 1 | 1 | 1 |
| | | CLST1 | 2 | 2 | 3 | 4 |
| | | ENFE1 | | | 2 | 3 |
| | | RDTME3 | 3 | 3 | | 5 |
| | | ENFE2 | 4 | 4 | 4 | |
| | | ENFE3 | 5 | 5 | 5 | 7 |
| | | USFIC4 | 6 | 7 | | 2 |
| | | TEF2 | | 6 | 6 | 6 |
| | | TEF1 | 7 | 8 | 7 | 8 |
| | | SDS3 | | 9 | | |
| | | CLST3 | | | | |
| | | CLST4 | | | | |
| | | CLST6 | | | | |
| ENG4 - Radionuclide Release Rates and Solubility Limits | **OPEN** | ENFE3 | 1 | 1 | 1 | 1 |
| | | ENFE4 | 2 | 2 | 2 | 2 |
| | | CLST5 | 3 | 3 | 3 | 3 |
| | | ENFE5 | | | | |
| | | CLST3 | | | | |
| | | CLST4 | | | | |
| | | CLST6 | | | | |
| UZ1 - Climate and Infiltration | **CLOSED** | USFIC1 | | | | |
| | | USFIC2 | | | | |
| | | USFIC3 | | | | |
| | | SDS3 | | | | |

Closed

Closed Pending

More Impact
1
2
3
4
5
6
7
8
Less Impact

## Table 6. Status of resolution in model abstraction (cont'd)

| Integrated Subissue | Integration | Associated KTI Subissues | Data and Model Sufficiency | Data Uncertainty | Model Uncertainty | Model Support |
|---|---|---|---|---|---|---|
| UZ2 - Flow Paths in the Unsaturated Zone | **OPEN** | USFIC4 | **1** | **1** | | **1** |
| | | ENFE1 | | **2** | **1** | **2** |
| | | TEF1 | **2** | **3** | | |
| | | TEF2 | **3** | **4** | **2** | **3** |
| | | RDTME3 | **4** | **5** | **3** | |
| | | SDS3 | | **6** | | |
| | | RDTME2 | | | | |
| UZ3 - Radionuclide Transport in the Unsaturated Zone | **OPEN** | USFIC4 | **1** | **1** | **1** | **1** |
| | | RT1 | **2** | **2** | **2** | **2** |
| | | RT3 | **3** | **3** | **3** | **3** |
| | | SDS3 | | **4** | | |
| | | ENFE4 | | **5** | | **4** |
| | | USFIC6 | **4** | **6** | **4** | **5** |
| | | RT4 | | | | |
| SZ1 - Flow Paths in the Saturated Zone | **OPEN** | USFIC5 | **1** | **1** | **1** | **1** |
| | | SDS3 | **2** | **2** | **2** | **2** |
| | | USFIC2 | | | | |
| | | SDS1 | | | | |
| SZ2 - Radionuclide Transport in the Saturated Zone | **OPEN** | USFIC5 | **1** | **1** | **1** | **1** |
| | | USFIC6 | **2** | **2** | **2** | **2** |
| | | RT1 | **3** | **3** | **3** | **3** |
| | | RT2 | **4** | **4** | **4** | **4** |
| | | RT3 | **5** | **5** | **5** | **5** |
| | | SDS3 | | **6** | | |
| | | RT4 | | | | |
| Direct1 - Volcanic Disruption of the Waste Packages | **OPEN** | IA2 | **1** | **1** | **1** | **1** |
| | | CLST2 | **2** | **2** | **2** | **2** |
| | | CLST1 | **3** | **3** | **3** | **3** |
| | | SDS1 | | | | |
| Direct2 - Airborne Transport of Radionuclides | **OPEN** | IA2 | **1** | **1** | **1** | **1** |
| Dose1 - Dilution of Radionuclides in Groundwater Due to …. | **OPEN** | USFIC5 | **1** | **1** | **1** | **1** |
| Dose2 - Redistribution of Radionuclides in Soil | **OPEN** | IA2 | **1** | **1** | **1** | **1** |
| Dose3 - Lifestyle of the Critical Group | **OPEN** | ISI-specific | **1** | **1** | **1** | **1** |
| | | USFIC5 | **2** | | | |
| | | RT3 | **3** | | | |
| | | IA2 | **4** | **4** | **4** | **4** |
| | | USFIC1 | | | | |
| | | USFIC2 | | | | |
| | | USFIC3 | | | | |

Closed

Closed Pending

More Impact
**1**
**2**
**3**
**4**
**5**
**6**
**7**
**8**
Less Impact

The concerns relate to the five model abstraction generic acceptance criteria in the YMRP. The acceptance criteria include: (i) Data and Model Justification (Criterion T1); (ii) Data Uncertainty (Criterion T2); (iii) Model Uncertainty (Criterion T3); (iv) Model Support (Criterion T4); and (v) Integration (Criterion T5). Note that although the acceptance criteria and review methods are applied to individual ISIs the intent of criterion T5 is to emphasize the appropriate interfaces among two or more ISIs. In an attempt to be more explicit on the integration aspect, to the extent feasible, potential important interfaces among the various ISIs are identified with the description of each ISI. Successful application of criterion T5 ensures that consistent assumptions, data, and models have been implemented in the TSPA. The reader should refer to the relevant KTI IRSRs for more detailed discussions and a path to resolution for acceptance criteria T1 to T4. Section 5.3.2 provides a more detailed discussion of integration concerns identified by the NRC PA staff.

Review of draft versions of some PMRs and information obtained via other sources, such as technical exchanges and Appendix 7 meetings, raised the concern of data falling outside the range of the results of a process model. When the process model is abstracted into PA, the data that fell outside the range are then omitted from the abstraction. If the abstraction of a process has heavy reliance on modeling due to difficulties in collecting data, the abstraction should incorporate both the results of the modeling and the available sparse data or justification should be provided if it does not. For example, pH measurements collected during the drift-scale heater test fall outside the range of pH values generated via modeling of the near-field geochemical environment. In addition, porosity and permeability changes have been observed during some of the thermal testing, yet the conclusion is drawn in the Abstraction of Drift Seepage AMR (CRWMS M&O, 2000k) that THC effects on seepage do not need to be included in the abstraction for PA with the technical basis being minimal observed changes during modeling of the process. Better justification for the selection of data abstracted into the PA is needed. This item will be tracked as a potential discussion point for upcoming technical exchanges. It is possible to select subsets of the data available to support a model. However a technical basis for usage or omission of a subset of data is required, especially when the models can only be calibrated and cannot be validated.

The TSPA-VA had a number of parameters that were represented as having variability and were sampled. It also had a large number of parameters that were set as constants. While it is obvious that some parameters can be represented as constants, it is not always intuitive in a complex system which parameters should be constant. In addition, if the system changes significantly (design, model, and data changes), it may be necessary to re-evaluate which parameters need to be sampled and which do not. This concern will be evaluated in the TSPA-SR and discussed at future TSPA technical exchanges.

Review of the Unsaturated Zone Flow and Transport PMR (CRWMS M&O, 2000l) by the TSPAI staff raised a concern about the selection of ACMs. In the Total System Performance Assessment—Site Recommendation Methods and Assumptions document (CRWMS M&O, 1999a), it is clearly stated that (p. 3-15) either the most conservative of two ACMs will be used in the TSPA-SR, or both will be used weighted by their relative likelihood. The context was in reference to how flow occurs within/near perched water bodies. As Open Item OSC0000001347C098 indicates, it is acceptable to apply this approach (of weighting) if adequate technical bases exists. In the UZFT PMR, approximately 20 alternate views are presented in an introductory table titled, “Summary of Current Understanding.” It is essential that the NRC staff be able to easily evaluate the relevant ACMs to assess the appropriateness of the selected ACM (if the selected model is nonconservative to performance compared to the models that are not selected). It is not always intuitive which model may be the conservative choice. This item will be a discussion topic for future technical exchanges.

Calculation integration and averaging have been discussed in previous versions of the TSPAI IRSR. Information transfer among components of the system may involve some sort of averaging when proceeding from different numerical grids (temporally or spatially or both). Technical basis is needed for any reduction in minima or maxima and changes to the shapes of distributions that result from the numerical representation. Threshold-type phenomena (such as a threshold seepage concept or cladding failure due to elevated temperatures) can be particularly susceptible. This item will be evaluated for TSPA-SR upon receipt of the GoldSim® code and the TSPA-SR documentation. It may be discussed at future interactions between the NRC and DOE.

The following paragraphs discuss the current status of resolution of Open Items relating to multiple model abstractions included in prior revisions of the TSPAI IRSR. Open Items for which there is agreement between NRC and DOE staff members have been closed. Open Items that have not been closed are discussed to indicate the current NRC staff understanding of the issue involved. Discussion points that have been raised at recent technical exchanges between NRC and DOE staff are also addressed (See Table 1 for a summary of Open Items and Table 4 for a summary of discussion points).

Open Item OSC0000001347C098 indicates that it is not appropriate to weight alternate conceptual models according to judgment that they are correct (without an adequate technical basis) because this methodology may provide a nonconservative PA. TSPA-VA has largely addressed this issue by calculating performance separately for ACMs instead of lumping the alternate conceptual models into a single assessment of performance. However, in some areas, such as determining the probability of volcanism in the repository area, DOE continues to weight alternative conceptual models by the judgment about the degree of their correctness without a sufficient technical basis. Therefore, Open Item OSC0000001347C098 will remain open at this time.

#### 5.3.1.1 Degradation of Engineered Barriers

The discussions that follow for the DOE approach to abstracting degradation of engineered barriers into total system PA and NRC's evaluation of the abstraction were current as of the EDA-II design. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of degradation of engineered barriers.

Staff evaluation of transparency and traceability in model abstraction will require a review of all relevant AMRs and PMRs. Therefore, the review findings are not presented in this version of the IRSR.

##### 5.3.1.1.1 Description of the U.S. Department of Energy Approach—Degradation of Engineered Barriers

The design of the WP in the TSPA-VA was a 2-cm thick Alloy 22 inner container surrounded by a 10-cm thick A516 steel outer container (U.S. Department of Energy, 1998a). The purpose of the outer overpack was to provide structural strength, radiation shielding, and a predictable containment time determined by the uniform corrosion of the carbon steel. However, uncertainties in the corrosion mode of carbon steel may significantly reduce the expected lifetime of this barrier. Since the release of the TSPA-VA, several enhanced design alternatives (EDAs) have been proposed (CRWMS M&O, 1999c). The expected TSPA-SR design is the EDA-II that uses a 5-cm thick Type 316L stainless steel inner container with a 2-cm thick Alloy 22 outer container. The 316L stainless steel inner container is designed to provide mechanical strength necessary for WP handling and emplacement and to resist the consequences of rockfall or seismic events. No credit for corrosion resistance is taken for the inner Type 316L barrier. The DOE, however, may consider that a perforated Type 316L container will reduce the rate of transport of radionuclides following SNF dissolution. Because corrosion is the primary container failure mode, the performance of the Alloy 22 container is the most important factor affecting WP lifetimes in the 10,000-year performance period in both the VA and the EDA-II WP designs.

The DOE modeling of WP lifetime is performed using the WAste Package DEGradation (WAPDEG) code (Atkins and Lee, 1996; CRWMS M&O, 1995b; U.S. Department of Energy, 1998a). WAPDEG is a probabilistic code that runs stochastic simulations in which random values are sampled to represent parameters in the corrosion models for determining WP corrosion rates and WP lifetimes.

The DOE TSPA-VA focused on dry-air oxidation of carbon steel because this material was proposed for the outer overpack in the VA design (U.S. Department of Energy, 1998a). Dry-air oxidation of Alloy 22 was not considered in the VA design because the corrosion-resistant material was placed inside the carbon steel outer barrier. For the SR design, DOE considers that dry-air oxidation of the Alloy 22 WP outer barrier will occur when the RH of the repository environment is less then the critical RH ($RH_{critical}$) for the initiation of humid-air corrosion (CRWMS M&O, 2000h,m). The rate of dry oxidation is considered to be limited by mass transport of reacting species through the tightly adhering passive oxide film and is modeled assuming a parabolic growth law in which the film thickness is proportional to the square root of time. It is concluded that the oxidation rate is low and dry-air oxidation does not appear to limit WP lifetime.

Humid-air corrosion is assumed to occur when the RH is greater than the $RH_{critical}$ (CRWMS M&O, 1999c). The $RH_{critical}$ is based on the deliquescence point (lowest RH at which a saturated solution of the salt can be maintained at a given temperature) for sodium nitrate (CRWMS M&O, 1999c). At 20 °C the deliquescence point for $NaNO_3$ occurs at a RH of 75 percent. At 90 °C the deliquescence point is lowered to a RH of 65 percent. The DOE model of corrosion of the Alloy 22 WP outer barrier assumes that the corrosion rate and the distribution of corrosion rates under these conditions are the same as for aqueous corrosion and are independent of time (CRWMS M&O, 2000h).

Aqueous corrosion is classified into two corrosion modes—general corrosion and localized corrosion. General passive corrosion is assumed when the corrosion potential ($E_{corr}$) is less than the critical potential ($E_{critical}$) for the initiation of localized corrosion. The general corrosion rates are derived from data obtained from the long-term corrosion test facility (LTCTF) where numerous test specimens have been exposed to aqueous solutions based on modifications of J-13 water (CRWMS M&O, 2000m; McCright, 1998). Corrosion rates of specimens exposed in the LTCTF were calculated by measuring the weight loss of the specimens (American Society for Testing and Materials, 1997) after exposures of at least 6 months. Data from specimens with weight gains were not used to determine the distribution of corrosion rates that ranged from 0 nm per year$^{-1}$ at the 0$^{th}$ percentile, 27 nm per year$^{-1}$ at the 50$^{th}$ percentile, 98 nm per year$^{-1}$ at the 90$^{th}$ percentile, and 730 nm per year$^{-1}$ at the 100$^{th}$ percentile. The abstracted general corrosion rate for the Alloy 22 WP outer barrier was reported to be distributed between $10^{-6}$ and $7.3 \times 10^{-5}$ mm per year$^{-1}$.

An enhancement factor, normally distributed between 1 and 2.5, is used to model the corrosion rate of thermally aged Alloy 22 and is based on the passive current density of a thermally aged specimen (700 °C for 173 hours) measured in a potentiodynamic polarization test (CRWMS M&O, 2000a). Acceleration of the corrosion rates as a result of microbial activity is also treated using an enhancement factor, $G_{MIC}$. For Type 316 nuclear grade, a $G_{MIC}$ of 10 is used based on results obtained with Type 304 SS. For Alloy 22, experimental results indicate a $G_{MIC}$ of 2 based on the corrosion rate measured in short-term exposure tests (CRWMS M&O, 2000h,m).

Localized corrosion of Alloy 22 is assumed to occur when the corrosion potential is greater than the critical potential. Critical potentials for localized corrosion of Alloy 22, reviewed in the general corrosion and localized corrosion of WP outer barrier AMR (CRWMS M&O, 2000m), are limited to pitting repassivation potential data obtained using a lead-in-pencil geometry (Gruss, et al., 1998). Initiation and repassivation potentials (as a function of temperature) were obtained in cyclic potentiodynamic polarization (CPP) tests using a variety of electrolytes (based on modifications of J-13 water). The same potentials were used as values for $E_{\mathrm{critical}}$ (obtained from anodic polarization curves). Although $E_{\mathrm{critical}}$ for a thermally aged specimen was reduced by 100 mV, the susceptibility of the thermally aged specimens to localized corrosion was not increased with respect to the base alloy because it is assumed that the corresponding reduction of $E_{\mathrm{corr}}$ will prevent the initiation of localized corrosion.

The rate of localized penetration of Alloy 22 was estimated using corrosion rates in highly corrosive environments. The distribution of localized corrosion rates is centered around the highest passive current density of 10 µA cm$^{-2}$ that corresponds to a corrosion rate of 100 µm per year$^{-1}$. The cumulative distribution of penetration rates for localized corrosion is 12.7 µm per year$^{-1}$ for the 0$^{th}$ percentile, 127 µm per year$^{-1}$ for the 50$^{th}$ percentile, and 1,270 µm per year$^{-1}$ for the 100$^{th}$ percentile (CRWMS M&O, 2000h,m).

The DOE has proposed two models for SCC susceptibility evaluation—the SCC threshold model and the slip dissolution/film rupture model (CRWMS M&O, 2000h). The SCC threshold model is based on fracture mechanics concepts, which suggest that for SCC to occur, the stress intensity ($K_I$) at a flaw or defect must be equal to or greater than the threshold stress intensity factor for the initiation of SCC ($K_{ISCC}$). A mean $K_{ISCC}$ value for Alloy 22 was measured to be 33 MPa m$^{1/2}$ using wedge-loaded precracked DCB specimens in a deaerated, acidic 5 wt % NaCl solution at 90 °C (Roy, et al., 1998; McCright, 1998).

Weld residual stress is the only type of stress assumed to be relevant under repository conditions in the SCC susceptibility evaluation conducted by the DOE. Finite element analyses of the outer barrier lid welds indicate that while the stress intensity factors associated with circumferential flaws are less than the $K_{ISCC}$, the maximum stress intensity factor for radial flaws may exceed the $K_{ISCC}$ (CRWMS M&O, 2000n).

The slip dissolution/film rupture model relates crack advance to the metal anodic oxidation that occurs when the protective film at the crack tip is ruptured as a result of a tensile stress. While it is suggested that these parameters can be determined from repassivation rate measurements under potentiostatic conditions, empirical data obtained for Types 304 and 316 SS in typical BWR environments and previous crack propagation rates for Alloy 22 are actually used to predict crack propagation rates as a function of $K_I$.

For both the slip dissolution/film rupture model and the SCC threshold model, through-wall radial cracking is predicted as a result of the high values of the calculated stress intensity factor. The approach adopted by the DOE to mitigate or eliminate the possibility of crack growth is to reduce the residual stresses associated with welding. One method consists of localized annealing of the weld region using induction heating. The other method proposed involves the use of laser peening to introduce compressive stresses on the surface using multiple passes of the laser beam (CRWMS M&O, 2000h).

Regarding the performance of the drip shield, which is one of the principal factors in the DOE postclosure safety case, the DOE is examining the possible environments to which the drip shield may be exposed (e.g., temperature, chemistry of incoming water) and evaluating the effects of these conditions on the possible failure modes and rates for Pd-bearing Ti alloys (in particular Ti Grades 7 and 16). The failure modes that have been considered include environmentally assisted cracking (EAC), consisting of SCC and HE or hydride-induced cracking (HIC), uniform corrosion, and localized corrosion (pitting and crevice). Thermal embrittlement was excluded based on FEPs screening (CRWMS M&O, 2000h).

Ti Grade 16 coupons were exposed for a period of 1 year under a variety of environmental conditions. The tests showed that there was little influence of temperature from 60 to 90 °C nor was there a significant influence of testing environment, with all tests being conducted in variants of J-13 well water. A wide variation in the measured weight loss (resulting in corrosion rates of approximately −1,700 to 150 nm per year) was observed (CRWMS M&O, 2000h), with similar results observed using creviced coupons (with no significant crevice corrosion). The variability in measured weight loss was explained as resulting from differences in the post-exposure cleaning procedures used to remove corrosion product buildup. Based on the maximum corrosion rates observed (350 nm per year for creviced specimens), it was concluded that failure of a Ti drip shield would be unlikely within the 10,000-year performance period.

Environmentally Assisted Cracking (EAC) was examined in two main parts—SCC and Hydrogen Induced Cracking (HIC). Analysis of these failure modes was based on the assumption that backfill would be present in the repository and thus precluded the possibility of increased stresses associated with rock fall. Since the issuance of the PMR on WP degradation Revision 00 (CRWMS M&O, 2000h), and even noted in the introduction of the PMR, the backfill option is no longer being considered. Because no new information on the effects of its removal is currently available from the DOE, this discussion considers only the situation in which backfill is still included. The PMR (CRWMS M&O, 2000h) and corresponding AMR (CRWMS M&O, 2000o) made a clear distinction between SCC and HIC. Within this framework, SCC was precluded as a likely failure mode given that the stress levels would be insufficient for SCC to occur due to the presence of backfill. The approach taken by DOE to evaluate HIC is based on the assumption that the dominant cathodic reaction occurring on the metal surface during passive (uniform) dissolution is hydrogen evolution and is assigned a reaction rate equal to the passive dissolution rate observed from coupon testing. Of the hydrogen gas produced from this cathodic reaction, a fraction (between 0.02 to 0.10) will enter into the metal as hydrogen atoms, which will then lead to a loss in ductility (i.e., embrittlement) after a critical hydrogen concentration has been exceeded. Based on the uniform corrosion rates observed from coupon testing and the assumptions involved with the fraction of hydrogen that is eventually adsorbed into the metal lattice, HIC was concluded not to have a significant effect on drip shield life expectancy during the 10,000-year performance period.

Recent computations for the EDA-II design, in which a Ti-grade 7 drip shield is included, exhibited a significant delay in the first WP failure, which occurred at approximately 100,000 years (Howard, 1999). In addition, the median WP lifetime increased to almost 400,000 years, and 90 percent of the WPs failed after 1,000,000 years. However, similar to the calculations of the TSPA-VA (U.S. Department of Energy, 1998a), these extremely long WP lifetimes are based on limited data on corrosion rates of Alloy 22 determined using gravimetric methods under experimental conditions in which no distinction can be established between uniform or localized corrosion processes.

#### 5.3.1.1.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Degradation of Engineered Barriers

Staff defines “engineered barriers” as any man-made component helping to reduce or stop the rate of radionuclide release. Thus, cladding, waste package, drip shields, and inverts are part of the EBS. The discussion that follows applies to issues of the EBS.

Parabolic growth of an oxide film has been observed when the nickel oxide thicknesses are greater than 3 to 4 nm (Fehlner, 1986). The assumption of parabolic growth of oxides on SS and Ni-Cr-Mo alloys is not supported by either DOE data or independent tests performed outside the HLW disposal program. However, parabolic oxidation kinetics result in greater oxide penetration compared to either logarithmic or inverse logarithmic kinetics (Fehlner, 1986).

The approach used by DOE assumes the formation of uniform oxide film and does not consider the possible preferential oxidation along grain boundaries. Intergranular oxidation has been observed at temperatures above 600 °C on a Fe-10 Cr-34Ni alloy (Newcomb and Stobbs, 1991) and in the range of 800 to 1000 °C for Alloys 800H and 825 (Wei and Scott, 1989).

The approach used by DOE, assuming that the corrosion rates under humid air conditions are the same as those under aqueous conditions, appears to be conservative as indicated. A comparison of aqueous and humid air corrosion rates for type 316L (CRWMS M&O, 2000h) reveals that the humid air corrosion rates are almost an order of magnitude less than the aqueous corrosion rates. The use of the deliquescence point for $NaNO_3$ as the criteria for the $RH_{critical}$ is supported by a review of empirical data (CRWMS M&O, 2000p). Other salts that may be deposited on the surfaces of the WPs have deliquescence points corresponding to higher values of RH.

The DOE approach relies on passive dissolution rates of Alloy 22 determined via weight loss measurements. In the case of the DOE LTCTF data, the deposition of silicate was shown to interfere with weight loss data. The suggested correction (CRWMS M&O, 2000h,m) to the corrosion rate distribution (i.e., addition of 63 nm per year$^{-1}$) is not acceptable because it does not account for the time-dependent changes in corrosion rate that must have occurred after the silicate deposition. The distribution of passive corrosion rates used by the DOE is not supported by the electrochemical measurements conducted within the YMP program and is lower than corrosion rates measured in a variety of service environments. The corrosion rate data used by the DOE do not consider the effects of long-term changes to the composition of the oxide films. Previous investigations (Lorang, et al., 1990) have indicated that the composition of the oxide film, which acts as a barrier for mass transport, becomes enriched in Cr and depleted in Mo and Ni.

The enhancement factor for the thermally aged specimens is based solely on short-term data and does not consider the effects of preferential corrosion that may occur at the grain boundary regions as indicated in previous investigations (Heubner, et al., 1989). The enhancement factor for MIC, $G_{MIC}$, was calculated from the results of exposures to sterile and inoculated solutions (CRWMS M&O, 2000h,m). No information is provided on the possible preferential dissolution of alloying elements as a result of microbial activity. In addition, the effect of temperature on the value of $G_{MIC}$ is not available.

Localized corrosion rates assumed by the DOE, obtained from literature data using acidic chloride and acidic oxidizing chloride solutions, appear to correspond to measured localized corrosion penetration rates obtained in service environments, as reviewed by Cragnolino, et al. (1999).

The validity of $K_{ISCC}$ as a bounding parameter for performance should be assessed through an appropriate combination of experimental and modeling work. As previously reviewed (Cragnolino and Sridhar, 1992), $K_{ISCC}$ values ranging from approximately 8 to 20 MPa $m^{1/2}$ have been observed for Types 304, 304L, 316, and other similar austenitic SS in chloride-containing solutions at temperatures ranging from 80 to 130 °C. As expected, the values in the lower end of that range are observed with both increasing temperatures and chloride concentration.

In addition to environmental effects, the DOE evaluation of the SCC susceptibility of Alloy 22 has not considered the effects of variations in material properties, heat-to-heat differences, fabrication and welding, and long-term exposure to elevated temperatures. These variations are not easily correlated with compositional variations or differences in mechanical properties. Segregation of alloying elements and the formation of TCP phases in the welded regions has been shown to occur for Alloy 22 (Cieslak, et al., 1986) and thermal aging has been shown to increase the localized corrosion susceptibility (Heubner, et al., 1989). Long-term exposure of the WP to elevated temperatures expected in the proposed repository may result in microstructural alterations that may be equivalent to aging for 100 hours at 700 °C (CRWMS M&O, 2000h).

Though data have been obtained examining the possibility and rates associated with uniform and localized corrosion of some Ti-Pd alloys to be used for the drip shield, confirmation of the low corrosion rates measured in weight loss experiments is needed. This confirmation is particularly important as there appears to be an inconsistency between the AMR on general and localized corrosion (CRWMS M&O, 2000q) and the PMR (CRWMS M&O, 2000h). The AMR claims that the weight loss measurements are at or below the reliable detection limit yet these values are utilized for life-prediction purposes in the PMR. Of possibly greater importance is the lack of experimental work examining the possible detrimental effects of fluoride on the corrosion behavior of Ti. Though present in some test environments at low levels, the presence of other species, such as Ca and Si, limit the concentration of free fluoride available for complexation with Ti (Schutz and Grauman, 1985).

From the perspective of localized corrosion, though little or no localized corrosion has been observed thus far, the localized corrosion behavior of Ti-Pd alloys has not been extensively studied. It has been observed that, under relatively aggressive conditions, these materials still exhibit very high crevice corrosion resistance (Brossia and Cragnolino, 2000a). In the presence of fluoride, however, significant attack has been reported. In fact, crevice corrosion has been observed in chloride/fluoride environments (Brossia and Cragnolino, 2000b). In addition, the possible detrimental effects of fabrication methods, such as weldments, have not been evaluated.

Though not considered important by the DOE, thermal embrittlement of Ti alloys has been reported based on thermally driven redistribution of nearly insoluble impurities from grain interiors to grain boundaries (Nesterova, et al., 1980), with embrittlement noted at temperatures as low as 350 °C after 500 hours. However, the possibility of embrittlement at lower temperatures when exposed for longer periods has not been examined. In addition, the effects of a decrease in the yield strength and the ultimate tensile strength of Ti grade 7 at elevated temperatures (at 250 °C yield strength and ultimate tensile strength values close to half of those at room temperature are observed) on mechanical integrity have not been evaluated.

EAC of Ti-Pd alloys has not been extensively examined. The use by the DOE of the minimum hydrogen concentration necessary for HE based on commercial purity Ti is conservative. The technical basis for the fraction of hydrogen absorbed, especially considering the well-known catalytic properties of Pd for hydrogen generation, however, is unclear. In addition, the reliance on the passive corrosion rates measured from weight loss coupons is a matter of concern. The corrosion rates measured (approximately ten to a few hundreds of nm/y) using weight loss methods, especially given the uncertainties concerning cleaning procedures, may be unreliable and nonconservative. It is unclear why these results were then used for performing the hydrogen concentration analyses if this is the case. Furthermore, based on electrochemical corrosion tests, much higher passive dissolution rates were observed (at least a factor of 30 larger and in some cases over 400 times larger), which could lead to a more conservative estimate of the hydrogen concentration in the alloy after 10,000 years, which, in turn, may suggest that HE of Ti is possible under anticipated repository conditions.

#### 5.3.1.2 Mechanical Disruption of Engineered Barriers

The discussions that follow for the DOE approach to abstracting mechanical disruption of engineered barriers into total system PA and NRC’s evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC’s evaluation of DOE’s approach to abstraction of mechanical disruption of engineered barriers.

##### 5.3.1.2.1 Description of the U.S. Department of Energy Approach—Mechanical Disruption of Engineered Barriers

The current DOE approach to the mechanical disruption of engineered barriers is limited to analyses of the direct and indirect effects of earthquake-induced rockfall on WPs (U.S. Department of Energy, 1998a). In the DOE VA report, direct effects refer to possible breach of WPs from rockfall. Indirect effects refer to rockfall-enhanced corrosion and rockfall-induced damage to fuel rods and assemblies. The DOE concludes that the WPs are robust and sufficiently resistant to corrosion such that any rockfall within the 10,000 year regulatory period will not cause or enhance premature release of radionuclides.

Section 10.5.1 of the Technical Basis Document for Viability Assessment (TBD VA) (TRW Environmental Safety Systems, Inc., 1998) specifically addresses the rockfall model, which describes the likelihood of earthquake-induced rockfall, potential size of rockfall, and the consequences to WP integrity and radionuclide releases. The possible effects of seismic disturbance (vibratory ground motion or fault displacement) include rockfall damage to WPs and change in flow pattern near the emplacement horizon. From DOE's perspective, rockfall is expected to be the primary source of indirect WP disturbance (not WP failure, however).

The TBD VA calculated WP damage for four time periods: 0 to 1,000 years; 0 to 10,000 years; 0 to 100,000 years; and 0 to 1,000,000 years. In each time period, 500 event times were randomly drawn (TRW Environmental Safety Systems, Inc., 1998, Section 10.5.1.6). Consequently, the event frequency for each time period is 0.5 event per year, 0.05 event per year, 0.005 event per year, and 0.0005 event per year, respectively.

In determining the rockfall model source term, "the fall of a single rock size (the largest possible for the PGV selected) per event" (TRW Environmental Safety Systems, Inc., 1998, Section 10.5.1.6) was modeled. The TBD VA states that, "clearly, many rocks fall during an earthquake. Future analyses will incorporate multiple rockfalls into the integrated corrosion-rockfall WP degradation model."

The DOE model of rockfall is based on a four-step flow-down scenario: (1) the availability of sufficiently large blocks that could fall and damage or breach WPs; (2) the probability of generating rockfall from seismic shaking; (3) the susceptibility of WPs to cracking, taking into account corrosion-induced thinning of the WP walls; and (4) the likelihood of rockfall hitting the WPs given the layout of WPs in the drifts. The DOE considered two options in this scenario, one in which a through-going crack causes WP failure (breach) and one in which rockfall starts a crack that becomes a locus for enhanced corrosion. The rock size necessary to cause these two types of damage was estimated by dynamically modeling the rockfall impact on WPs (CRWMS M&O, 1996a,b) using 3D finite element analyses. Degradation (thinning as a result of corrosion) of WPs was considered in the rockfall model (CRWMS M&O, 1996a,b).

(1) The DOE derived the distribution of large blocks from fracture spacing data based on detailed fracture mapping of the Exploratory Studies Facility (ESF) (U.S. Department of Energy, 1997a). Fractures were mapped in the Exploratory Studies Facility, primarily in the middle nonlithophysal unit of the Topopah Springs tuff. Block volumes were estimated from the fracture data and converted to a rock mass by assuming a rock density of 2.297 g/cm$^3$. The falling rock blocks were assumed spherically shaped.

(2) The amount of rockfall was correlated with seismic ground shaking by the empirical relationship of Kaiser, et al. (1992). This relationship predicts a so-called damage level (DL) as a function of peak ground velocity. The empirically derived relationship is based on observations of rockfall from rock bursts in underground mines. DL is an arbitrarily defined scalar value that ranges from DL1—minor cracking and spalling to DL5—severe damage. The DOE modified the Kaiser, et al. (1992) equation to account for initial rock conditions (TRW Environmental Safety Systems, Inc., 1998, Equation 10-11), under the assumption that, for the same level of ground shaking, rocks with initially good rock conditions will produce significantly less damage (lower DL values) than rocks with initially average or below average rock conditions (higher DL values). The initial rock conditions parameter used to modify Kaiser's equation is a measure of rock wall quality, failure potential, local mining stiffness, and support effectiveness (all factors considered in mining engineering analyses of tunnel stability). Additional factors accounted for in the initial rock condition parameter are rock quality and temperature.

The DOE extrapolated peak vertical ground velocity from the DOE Probabilistic Seismic Hazard Analysis (PSHA) (U.S. Geological Survey, 1998). For the analysis, the DOE used the median hazard with the 85$^{th}$ and 15$^{th}$ quantiles. Peak horizontal velocities were converted from peak horizontal accelerations in the 5–10 Hz range of the ground acceleration frequency spectrum. Horizontal velocities were converted to vertical velocities assuming a simple 2/3 scaling factor. This conversion was necessary because the DOE PSHA (U.S. Geological Survey, 1998) was developed for a site on bedrock at the level of the repository. The resulting PSHA hazard does not account for possible soil or shallow crustal amplification or deamplification. Those amplification factors are still under debate. The DOE indicates that they will provide final and complete PSHA values in the upcoming Topical Report #3.

(3) In the TSPA-VA (U.S. Department of Energy, 1998a), rockfall image is modeled by assuming that any rock larger than the crack-initiation value for a given wall thickness causes an enhancement in the corrosion rate as a result of localized corrosion. The extent of enhancement is given by the amount the rock mass exceeds the crack-initiation threshold. If a rock larger than that required to create a through-wall crack falls on the WP, it is assumed that the package is breached.

In the TSPA-VA (U.S. Department of Energy, 1998a), structural failure of WPs due to rockfall was not included in the basecase. Auxiliary analyses, which considered the thinning of both the carbon steel outer container and the inner container as a result of corrosion, were conducted using Alloy 625 instead of Alloy 22 as inner container material. It was concluded the WP maintains containment even when the entire outer container and more than half the wall thickness of the inner container have been removed because of corrosion. The decrease in wall thickness due to corrosion was computed by using the WAPDEG code (Atkins and Lee, 1996; TRW Environmental Safety Systems, Inc., 1998). Although Alloy 625 was used in the structural failure analysis, it is stated by the DOE that the analysis could be applicable to Alloy 22 (U.S. Department of Energy, 1998a).

(4) In the VA, the DOE assumed a loading density of 83 MTU/acre and WP distributions and drift dimensions given in the reference design (U.S. Department of Energy, 1998a). Based on these assumptions, the likelihood of a rockfall hitting a WP is 0.40. In addition, the DOE assumed that the WPs will remain exposed to potential rockfall failures throughout the period of concern, despite the possibility that the drifts may be filled with small rocks and debris. The DOE contends that such small rocks and debris may act as a natural backfill barrier that could protect the WPs from any subsequent damaging rockfall.

DOE did not consider the potential consequences of other aspects of the ISI. The DOE contends that the probability of direct fault disruption of the repository is too small ($1 \times 10^{-8}$ per year) to require consequence analyses.[11]

The DOE also claims that rockfall from the TM stresses during the thermal pulse will occur early in the repository postclosure phase (within the first 100 years), such that associated rockfall will contact intact and robust (uncorroded) WPs. The DOE claims that such robust WPs can withstand any potential rockfall. The DOE also assumes that concrete liners will decompose within a few hundred years and should not be considered a factor in rockfall calculations.

[11]DOE/NRC Appendix 7 Meeting, Las Vegas, Nevada, August 1998.

DOE's TSPA-VA (U.S. Department of Energy, 1998a) attempted to perform more detailed modeling than previous TSPAs regarding the interaction of magma with the WP. Details of the DOE approach are presented in the IA IRSR (U.S. Nuclear Regulatory Commission, 1999i). The most important processes used by the DOE to model igneous disruption of the WP are

- Magma entering a nonbackfilled repository drift would contact two WPs per drift
- WPs in contact with magma are breached
- HLW from the breached WPs can be dissolved in the basaltic magma

The DOE concluded in the TSPA-VA that intrusive disruption of the proposed repository site (i.e., enhanced source-term analysis) would have a negligible impact on repository performance during the first 10,000 years after postclosure, and this magmatic disruption does not affect the principal factors identified in the TSPA-VA (U.S. Department of Energy, 1998a).

In its Disposal Criticality Analysis Methodology Topical Report YMP/TR–004Q (U.S. Department of Energy, 1998e), DOE indicated that "the effects of external events such as WP orientation, rockfall, or seismic activity have on the integrity of the undegraded internal components and FWF, and on the location of the corrosion products" will be considered. DOE has proposed to analyze the effects of these events, which include seismicity, to be considered "at appropriate intervals in the progress of the geochemical process." As a result of the NRC's comments on the DOE approach, DOE is planning to analyze the direct effect of seismicity on the in-package criticality consequence of reshuffling a single SNF assembly in the WP.

#### 5.3.1.2.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Mechanical Disruption of Engineered Barriers

The DOE approach, as documented in the VA, is no longer representative of repository performance related to this ISI. First, newly proposed design changes (U.S. Department of Energy, 1999b), including partially backfilled drifts, protective drip shields, and WP composition alters the underlying abstractions in the consequence models. For example, the mitigating effects that partial backfill may have on rockfall concerns have yet to be quantified. In addition, even if the backfill were to become cemented over time, its structural influence may be inconsequential because it will have a relatively weak structural strength compared to the surrounding intact rock and WP materials. Second, the abstractions of the vibratory ground motion results need to be corrected for shallow crustal and soil amplification factors.

The level of damage and amount of rockfall as a result of vibratory ground motions depend heavily on the related rock mass conditions (rock types), state of stresses, and ground supports. The empirical equation used in the TBD VA to estimate the damage to underground excavations caused by shaking was developed for assessing rockburst-induced tunnel damage for underground mines in Sudbury, Ontario, Canada, and is qualitative in nature. Consequently, applicability of the DL assessment empirical equation to the YM site needs to be verified.

The annual probability of exceedance curve for horizontal peak ground velocity (PGV) used to sample the PGV for estimating rockfall was based on the Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada, Final Report, dated June 15, 1998 (U.S. Geological Survey, 1998). It was not clear in the TBD VA whether DOE used the mean or the median PGV in the analysis of the WP disruption. In the text, DOE discusses the median PGV, while the table lists the mean PGV. DOE needs to clarify the PGV values used in their analysis.

The dynamic finite element analyses conducted for assessing rockfall effects does not take into consideration the vertical velocity of the WP and the initial velocity of the rock when it becomes dislodged due to the seismic ground motion. Another area of concern is the use of a maximum normal stress failure criterion to establish rupture of the WP outer barrier due to rockfall. Because of the complex nature of the 3D stresses experienced by the WP as a result of the rock block impact, the maximum-normal-stress theory is unable to account for the out-of-plane shear stresses that play a major role in the failure of ductile metals. As a result, it has been proposed that the precepts of fracture mechanics may be the most appropriate approach in establishing a more realistic failure criterion because it can take into account the effects of the surface flaws generated during the WP fabrication process.

In determining the rockfall model source term, “the fall of a single rock size (the largest possible for the PGV selected) per event” (TRW Environmental Safety Systems, Inc., 1998, Section 10.5.1.6) was modeled. This approach appears not to be conservative. The CRWMS M&O recognizes this and stated in the TBD VA that, “clearly, many rocks fall during an earthquake. Future analyses will incorporate multiple rockfalls into the integrated corrosion-rockfall WP degradation model.”

The contention that the probability of direct fault disruption of the repository is too small to require consequence analysis is not necessarily supported by results of the DOE PSHA (U.S. Geological Survey, 1998). This reference indicates that significant fault displacements could occur in the repository with a probability greater than $1 \times 10^{-8}$ per year.

Also, there are several noteworthy shortcomings to the DOE approach presented in the VA:

- Derivation of block sizes from the fracture data did not account for

  — Potential sampling biases inherent in the measured fracture spacing, number, and distribution of fracture sizes and fracture orientations (U.S. Nuclear Regulatory Commission, 1999f)

  — Fracture characteristics of the lower lithophysal unit of the Topopah Springs tuff, which will house nearly 70 percent of the repository

  — Mechanical properties of the tuffs that may lead to a larger yield zone above the drifts

  — Potentially damaging super blocks composed of multiple rocks that fall in unison

  — Initial wall collapse during the thermal pulse followed by a larger roof collapse during the cooling phase

- Abstraction of PSHA vibratory ground motion results does not account for correct shallow crustal and soil amplification factors and used the median not the mean hazard curves, despite agreement between the DOE and the NRC to the contrary (U.S. Department of Energy, 1997a). In the PSHA, the mean hazard is greater then the median. Moreover, the abstraction relies on empirical and subjective rockfall damage data from mining rock bursts. The relationship between rock bursts and earthquake damage is not well established.

- The possibility of accelerated localized corrosion of the outer carbon steel container is not properly considered in the TSPA-VA and therefore its eventual effect on the mechanical failure of the WP is not addressed. The detrimental effects of welding and thermal exposure on the phase stability and mechanical properties of Alloy 22 have been investigated by the DOE but the consequences of mechanical failure promoted by disruptive events are not addressed in the DOE PA calculations.

- Consistency was lacking for models used in mechanical disruption of engineered barriers by igneous intrusion calculations. Details of these concerns are presented in (U.S. Nuclear Regulatory Commission, 1999i). Summary concerns with the three most important processes concomitant with the igneous intrusion abstraction that was used by the DOE are

    — Magma is a pressurized, volatile-rich fluid that will expand and flow upon entering repository drifts. Many more WPs could be contacted by flowing magma than the two WPs assumed in the TSPA-VA analyses.

    — Although staff agree that WPs exposed to static basaltic magma are likely to fail through stress rupture and collapse, additional HLW fragmentation and mobilization is possible from the dynamic impact of flowing magma within the drift.

    — Models for HLW dissolution in the magma have not considered the kinetics of element mobility in basaltic melts. Dissolution rates in basalt may be lower than what was modeled, such that significantly more HLW is available for aqueous dissolution and transport through the fractured basalt.

Based on material presented in the TSPA-VA and supporting documents, staff conclude that many of the key process models used by DOE to evaluate intrusive disruption of the WP would not meet acceptance criteria presented in NRC (1999i). Although the expected annual dose from the HLW extruded in the accompanying volcanic event is likely many orders of magnitude larger than the groundwater dose, DOE will still need to present an acceptable analysis of intrusive disruption of the engineered barriers processes in their LA because this process has a nonnegligible contribution to total-system performance. Informal communications with DOE staff since the TSPA-VA was released have addressed many of these technical concerns with the igneous risk calculations. DOE staff appear to recognize the need to develop additional models and data to support future DOE TSPAs for IA. No changes to DOE performance models, however, were evident in the draft Environmental Impact Statement for Yucca Mountain (U.S. Department of Energy, 1999c).

In reviewing the DOE's Disposal Criticality Report YMP/TR–004Q (U.S. Department of Energy, 1998d), the NRC commented that DOE did not include the seismic event systematically in their approach for identifying the scenarios and configurations, which have potential for criticality. Furthermore, NRC has indicated to DOE specifically that they should evaluate the impact of seismic events on the consequences of transient criticality events. Reshuffling of the SNF assemblies within the WP and subsequent potential damage to the waste forms from reactivity step insertion has been identified as a specific example of impact of seismic events. DOE has indicated the specific in-package SNF configurations resulting from seismic events are application issues not appropriate for a methodology report such as the Disposal Criticality Report. However, it appears DOE has started to consider the seismically induced configurations, which will have the potential for the WP to be critical. The specific configurations and the analysis results are not available at this time.

#### 5.3.1.3 Quantity and Chemistry of Water Contacting the Waste Packages and Waste Forms

The discussions that follow for the DOE approach to abstracting the quantity and chemistry of water contacting the waste packages and waste forms into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of the quantity and chemistry of water contacting the waste packages and waste forms.

##### 5.3.1.3.1 Description of the U.S. Department of Energy Approach—Quantity and Chemistry of Water Contacting the Waste Packages and Waste Forms

The following approach is used in the TSPA-VA (U.S. Department of Energy, 1998a) to determine the quantity of water contacting the WP. MAI is used as a steady-state flux boundary condition to the dual-continuum, 3D UZ site-scale flow model. This UZ flow model is used during the various climate and infiltration scenarios to create maps of predicted deep percolation flux at any given location of the proposed repository horizon. For the TSPA-VA analyses, the repository flux maps are divided into six repository subregions of differing area-averaged deep-percolation flux rates (U.S. Department of Energy, 1998a). The flux rates for the six subregions are then used as boundary conditions in a drift seepage model. The drift seepage model uses a single-porous-media continuum approach. That is, the network of intersecting fractures in the proposed repository horizon is treated as a continuous porous medium. The process-level seepage model calculates two quantities for each of the six repository subregions used in TSPA analyses: (i) the fraction of WPs that receive dripping water (seepage fraction) and (ii) the flow rate of dripping water hitting wetted packages (seep flow rate). Uncertainty is handled by obtaining model results for nine different combinations of two key model parameters: fracture permeability and fracture van Genuchten alpha value. Each of the nine combinations of these two parameters is assigned a discrete probability of occurrence, such that the nine probabilities have a sum of one. DOE assumes that results obtained from the nine parameter combinations bound the realm of possible outcomes. The resulting ranges and probability distributions for the seepage fraction and the seep flux rate are independently sampled in DOE's TSPA code (U.S. Nuclear Regulatory Commission, 1999h).

DOE used a multi-scale modeling approach to abstract thermal-hydrologic processes into the TSPA-VA (U.S. Nuclear Regulatory Commission, 1999k). The multi-scale approach combines 1D, 2D, and 3D drift-scale thermal models and TH models with a conduction-only 3D mountain-scale model. These models were used in the TSPA-VA to estimate WP corrosion rates, waste-form dissolution rates, and the transport of RNs through the EBS. Repository heating is assumed to have a significant effect on seepage. To apply the seepage abstraction to a TH calculation, the DOE used a generalized equivalent continuum model with mean infiltration and nominal fracture van Genuchten alpha, for repository center locations. However, seepage was reduced to zero for the period of time that the temperature of the drift-wall above the WP exceeded boiling

(TRW Environmental Safety Systems, Inc., 1998). THM and THC alterations of hydrological properties were neglected for the basecase (U.S. Nuclear Regulatory Commission, 1999j).

DOE used the results of the WP degradation model in the TSPA-VA to determine the fractional area of the WP available for fluid entry (U.S. Department of Energy, 1998a). The WP degradation model included juvenile failures of WPs (assumed to be only one), and generalized and localized corrosion of the carbon steel outer barrier and the Alloy 22 inner barrier. The information used in the WP degradation abstraction included the design, temperature, RH, areal extent of dripping on an individual WP, pH of dripping water, and thresholds for corrosion initiation. An expert elicitation panel then derived the rates of container degradation. The time history of pit penetration (from localized corrosion) and patch penetration (from general corrosion) were the outputs of the model. Cumulative distribution functions that represented the first breach time distribution for the WP and the variation with time of the average number of pit and patch penetrations per failed WP (U.S. Department of Energy, 1998a) were then used in subsequent PA calculations. A patch size was assumed for a general corrosion penetration. The area of the corroded WP relative to the total area of the WP was used to determine the amount of water entering the WPs. Since the release of the TSPA-VA, DOE has indicated that the WP design will be the EDA-II design, with a stainless steel inner barrier and a C-22 outer barrier.

The amount of water contacting the commercial SNF waste form that could lead to a release of RNs was further reduced by assigning credit to the Zircalloy cladding. The undegraded cladding was assumed to completely protect the SNF from interaction with fluid. However, DOE incorporated a cladding degradation model (U.S. Department of Energy, 1998a). The cladding degradation model then calculated, in a manner similar to that used in the WP degradation model, the fraction of fuel exposed to water. DOE’s conceptualization of WP degradation led only to a flow-through path for water into and out of the WP.

DOE developed a set of five models to represent the near-field geochemical environment (U.S. Department of Energy, 1998a): (i) a description of the gas, water, and colloid composition coming into the drift; (ii) the composition of gas phase relative to the major gas sinks in the drift; (iii) the evolution of water composition reacting with major materials within the drift and the drift gas phase; (iv) a description of the stability and quantity of clay and iron-oxide colloids in the drift; and (v) the in-drift microbial communities. With the exception of the microbial communities and colloid model, these models were used to predict the chemistry of water contacting the WP and waste forms. Reaction of in-drift water and gas was calculated for different points along the flow-path of water. As a result, calculations of water and gas reacting with the concrete drift liner (not present in the EDA-II design), iron corrosion products, and SNF were completed. Calculation of the water composition was completed as a function of time, using six discrete periods: three during the boiling regime (0–2,000 years) and three periods that extend beyond to 100,000 years. Based on the different degradation rates of the different engineered materials (concrete, WP, and SNF) different sequential reactions (e.g., incoming water, concrete, WP, and then waste form) were used in the different time periods (U.S. Department of Energy, 1998a). The 2D TH model at the mountain-scale provided both the air mass fraction and gas fluxes through the drift as a function of time. These results included the effects of boiling and gas flow on the mix of air and steam in the gas phase, but none of the chemical interactions with the host rock. While 15 geochemical parameters describing the chemistry of water were calculated at various locations and at several different time periods, only the pH, ionic strength, and total carbonate concentrations were used in PA calculations. The chemistry of water contacting the WP calculated in these models was not used in the WP degradation model (U.S. Department of

Energy, 1998a). In addition, the chemistry of water expected inside the WP was not used in the cladding degradation models.

#### 5.3.1.3.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Quantity and Chemistry of Water Contacting the Waste Packages and Waste Forms

The DOE drift-scale process-level seepage model, used to calculate seepage fraction and seep flow rate for TSPA, does not include several potentially important processes and has not been shown to yield reasonably conservative upper bounding values. Review of the DOE drift seepage approach has identified inadequacies in the data, experiments used to collect the data, the models used to describe the seepage process, and the methods used to abstract seepage into PAs (Hughson, 1999; Drift Seepage Peer Review Panel, 1999; U.S. Nuclear Regulatory Commission, 1999h,j,m).

How much water enters the WP and contacts the waste form is a function of WP degradation and cladding degradation. Analysis of DOE's approach to WP degradation is presented in Section 4.3.1.1.1 (Degradation of Engineered Barriers ISI).

Analysis of DOE's approach to cladding degradation is presented in Section 4.3.1.1.4 (RN release and solubility ISI). DOE did not consider all pertinent failure mechanisms of SNF cladding and does not have adequate data to fully support performance claims of cladding as an additional metallic barrier to the release of RNs (U.S. Nuclear Regulatory Commission, 1999e,m). These observations indicate that DOE has not adequately supported its abstraction of the quantity of water that can enter the WP and contact the waste form. It is unclear whether DOE will be able to acquire sufficient data, applicable to conditions at the proposed repository, in time to demonstrate compliance with NRC requirements (Holonich, 1999).

Relative to prior PAs, DOE has made considerable progress in addressing the effects of coupled THC processes on performance in the TSPA-VA. Present limitations in these analyses are recognized and generally well documented by DOE, particularly in the TBD VA (TRW Environmental Safety Systems, Inc., 1998). Many alteration products of tuff and engineered materials are likely to affect the chemistry of water contacting WPs, which, in turn, can affect corrosion rates, waste form alteration rates, and RN solubility and speciation (U.S. Nuclear Regulatory Commission, 1999d). Although an effort was made to address this subject in the TSPA-VA, there are many limitations in the data used and the extent of phases considered (U.S. Nuclear Regulatory Commission, 1999d). Coupled THC processes that affect seepage were not considered explicitly in the TSPA-VA (U.S. Nuclear Regulatory Commission, 1999d). The effects of coupled THC processes that affect seepage are also important in characterization of the WP chemical environment. The bulk of the long-term data used in the abstraction of WP corrosion in the TSPA-VA may not be applicable to the environmental conditions at YM (U.S. Nuclear Regulatory Commission, 1999e,d). For example, models for the WP chemical environment were developed but not used in the abstraction of WP corrosion (U.S. Nuclear Regulatory Commission, 1999e,d). Data and models presented in the TSPA-VA used to calculate the chemistry of water contacting the waste forms were determined inadequate to describe the process under thermally-altered conditions (Holonich, 1999). Finally, models for the chemical environment for RN release were developed but not used in the abstraction of RN release from the glass waste form (U.S. Nuclear Regulatory Commission, 1999d).

The amount of data required for the LA and the need to confirm expected performance of the evolving repository system, will depend on the importance of the quantity of water contacting WPs and waste forms to the DOE safety case (Holonich, 1999).

#### 5.3.1.4 Radionuclide Release Rates and Solubility Limits

The discussions that follow for the DOE approach to abstracting radionuclide release rates and solubility limits into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of radionuclide release rates and solubility limits.

##### 5.3.1.4.1 Description of the U.S. Department of Energy Approach—Radionuclide Release Rates and Solubility Limits

The DOE modeling of this ISI was based on the assumption that the WPs were degraded. RNs are not available for release and transport until: (i) failure of the fuel cladding or HLW canister; (ii) degradation of the solid waste form; and (iii) mobilization of RNs into aqueous solution or an aqueous colloidal suspension. Mobile RNs are transported out of the degraded WP and through the EBS to the geosphere via one of two mechanisms: (i) movement of dissolved or colloidal material via diffusion or (ii) movement of dissolved or colloidal material via advection (U.S. Department of Energy, 1998a). The conceptual model used by DOE was composed of waste form degradation, RN mobilization, and transport through the engineered system. The components of the models include the initial inventory, degradation of the cladding on commercial SNF, dissolution rates from the waste forms, solubility constraints on RN mobilization, formation of colloids and secondary mineral phases, flow and diffusion of RNs through the engineered system, and sorption within the engineered system. DOE treated nuclear criticality scenarios, both in the WP and external to the WP, as a disruptive event.

The important input into the waste form degradation and mobilization models included the inventory of RNs. In addition, the temperature at the WP surface, RH at the WP surface, and liquid saturation in the invert beneath the WP, all derived from TH modeling results, were inputs to the models. Results from WP degradation, cladding degradation, water ingress into WPs, the amount of exposed fuel surface caused by cladding degradation, and the near-field geochemical conditions were also used as input to the waste form degradation and RN mobilization models. For the EBS transport model, parameters relating to the mobilization of RNs from the waste form, the flux and chemistry of the water moving through the system, and the retardation in and permeability of the EBS materials were used as inputs. The output for these three models is a release of RNs from the EBS into the geosphere.

DOE included commercial SNF, HLW as canistered borosilicate glass, DOE SNF, and plutonium waste forms in its inventory for the VA (U.S. Department of Energy, 1998a). Only nine RNs were used by DOE ($^{14}C$, $^{129}I$, $^{237}Np$, $^{231}Pa$, $^{239}Pu$, $^{242}Pu$, $^{79}Se$, $^{99}Tc$, and $^{234}U$) in their performance calculations.

The dissolution rate for commercial SNF was based on data from high-flow rate experiments, which yielded the intrinsic dissolution rate as a function of temperature, pH, total carbonate concentration, fuel burn-up, and oxygen fugacity. The rate was expressed as a mass dissolved from a surface area in a given time. The effective surface area was derived from experimental observations and accounted for fracturing of fuel pellets (U.S. Department of Energy, 1998a). The dissolution rate did not account for solubility limits or retention of RNs in secondary phases.

The glass waste form dissolution model was based on experimental evidence. The rate was a function of temperature, exposed surface area, solution pH, and dissolved silica concentration in solution. The DOE SNF dissolution model assumed a weighted RN inventory based on 6 of the 16 categories of DOE fuel. A metallic fuel model, which was a function of temperature, was used to describe dissolution for this type of waste.

The solubility-limit model used by DOE was a hybrid of solubility-limit distributions determined by expert elicitations, previous assessments, and a reassessment of measured neptunium concentrations (U.S. Department of Energy, 1998a). Using this approach, the concentration of each RN mobilized from the waste form cannot exceed the RN solubility limit, unless suspended colloids are included. The solubility limit was applied both within the WP and during the transport through the engineered barriers.

DOE's initial colloid analysis focused on plutonium because it is a major part of the waste inventory, has low solubility and high sorption onto the host rock and is anticipated to be the RN most likely affected by colloidal transport (U.S. Department of Energy, 1998a). Four types of colloids were chosen for explicit modeling: clay, iron corrosion products, SNF colloids, and glass waste colloids. DOE partitioned colloid transport behavior into two categories that were sampled. First, DOE assumed that Pu was reversibly attached to colloids (fast attachment and slow detachment), and colloids were not retarded during transport through the UZ. The second category assumed that Pu was irreversibly attached to colloids.

The effect of secondary minerals on RN release was only assessed in sensitivity studies (U.S. Department of Energy, 1998a). The sensitivity study focused only on the release of Np using a reactive-transport simulator. Two scenarios were evaluated: all of the Np released from schoepite (assumed to have the same uranium to neptunium ratio as the SNF) dissolution goes into aqueous solution; and release Np is also incorporated into other secondary uranium minerals with the same uranium to neptunium ratio. Simulations with different temperatures and cladding failures were conducted. The concentration of Np exiting the WPs was then used to constrain a Np solubility limit different from that assumed in the basecase analyses.

Transport in the EBS was modeled within the RIP using a series of mixing cells coupled by advective and diffusive connections (U.S. Department of Energy, 1998a). Diffusive transport from the WP was calculated for both pit and patch areas on the WP. The volumetric flux through the WP was calculated by scaling the seepage flux into the drift with the available surface area. The available surface area was derived from patch and pit failures. Transport through the invert, the structure that provides the support for the WPs, was by advection or diffusion. Diffusion for the invert was calculated for concrete with assumed 10 percent porosity and liquid saturation determined from TH calculations. Diffusive transport was calculated using an equation for diffusion in a partially saturated medium. Retardation of uranium, plutonium, neptunium, and protactinum in the invert was used and assumed that no degradation or reduction in permeability occurs.

Criticality both within the WP (in-package) and in the surrounding rock were assessed in the TSPA-VA (U.S. Department of Energy, 1998a). Using a series of sequential steps and associated analyses, the consequences of in-package criticality on RN inventory and the additional heat output from a steady-state criticality was predicted. DOE used reaction-path modeling calculations to conclude that the concentration of fissile material that could collect at a location external to the WP was too low to become critical (U.S. Department of Energy, 1998a).

#### 5.3.1.4.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Radionuclide Release Rates and Solubility Limits

The total radioactivity contained in the DOE SNF and HLW glass forms is small relative to that of commercial SNF. However, both the inventory of RNs and the rates at which RNs are released from these waste forms differ from that of commercial SNF. Thus, DOE should estimate the contribution of these waste forms to the dose limit. The types of waste [SNF (commercial and DOE) and other] evaluated by DOE in the VA were appropriate.

Although considerable uncertainties may exist regarding the grain boundary inventory of $^{99}$Tc, the current 2 percent approximation used in the TSPA-VA (U.S. Department of Energy, 1998a) may be conservative. It is important that the DOE determines accurately the prompt release of $^{99}$Tc because of its potential effect on early peak doses (U.S. Nuclear Regulatory Commission, 1999e). RNs important to system-level performance depend somewhat on the assumptions regarding the flow pathways, transport parameters, and dilution (Jarzemba and Pickett, 1995). NRC acknowledges the adequacy of DOE's selection of RNs important to performance. However, because detailed PA models and the RNs used by DOE and NRC (Mohanty and McCartin, 1998) differ, DOE should provide a rationale for deciding, which RNs are important for their contribution to dose in TSPA calculations. Resolution of the differences in the importance of specific RNs will depend on the effect on overall performance and the assumptions regarding RN distribution among gap, grain boundaries, and matrix, releases including solubility and co-precipitation of certain RNs in secondary U minerals, and transport, including stability of colloids and sorption (U.S. Nuclear Regulatory Commission, 1999e).

DOE's treatment of dry oxidation of the SNF and its effects on subsequent performance in an aqueous environment is satisfactory (U.S. Nuclear Regulatory Commission, 1999e). Both DOE's complete experimental program and their development of adequate process and abstracted models support this conclusion (U.S. Nuclear Regulatory Commission, 1999e).

Dissolution of SNF in aqueous environment was treated by DOE using the results of flow-through tests in sodium carbonate solutions. These are accelerated and conservative tests for the YM repository and do not involve formation of secondary minerals. In addition, chemical conditions in drip tests may be severe compared to actual conditions that will be created inside the WP, presumably giving rise to conservative estimations of dissolution rate compared with bathtub/immersion conditions. Some experimental results suggest that dissolution rates obtained under immersion conditions, in water containing Ca and Si, are lower than rates obtained from drip tests (U.S. Nuclear Regulatory Commission, 1999e). However, the drip test results in sodium carbonate solutions are similar to flow through test results. DOE should carefully examine the consistency among assumed dissolution rates from flow through tests, the measured RN concentration in the drip tests (which could be used to calculate the retention factors), and in the seismic-static tests (U.S. Nuclear Regulatory Commission, 1999e).

The chemistry of water in the WP is uncertain and DOE's treatment of this area is incomplete. The following environmental parameters and processes affect the dissolution rate of SNF: (i) pH of the aqueous environment; (ii) temperature; (iii) the nature and concentrations of the anionic species and other species [$Ca^{2+}$ and $SiO_2$(aq)] present in solution; (iv) corrosion of metallic components of the WP; (v) radiolysis; (vi) presence of low molecular weight organic products; and (vii) potential microbial processes (U.S. Nuclear Regulatory Commission, 1999d). The major limitation recognized by the NRC and DOE staffs is that although conceptually the complexity of coupled THC processes is recognized, many aspects of these processes are greatly simplified or omitted in the TSPA-VA analyses. Effects of the alteration of cladding and basket materials on the chemistry in the WPs controlling RN releases were omitted (TRW Environmental Safety Systems, Inc., 1998, Section 4.2.3.2.2). These effects could be important because both basket and cladding materials may have different compositions than the WPs. The additional materials could have a strong effect on corrosion products and associated water chemistry of the waste form environment. In addition, no process model exists for evolution of the gas phase chemistry within the drifts (TRW Environmental Safety Systems, Inc., 1998, Section 4.4.1). Neglect of these processes contributes to model uncertainty and should be justified or remedied. Other model inadequacies in the assessment of RN release are noted, including limitations of J-13 well water as a starting composition in the models, effects of condensation, water-rock interactions, nonisothermal chemistry, and engineered materials (U.S. Nuclear Regulatory Commission, 1999d). Nevertheless, DOE made considerable progress in addressing effects of coupled THC processes on the chemical environment for RN release in the TSPA-VA compared to prior TSPA activities. The stepped temporal changes in the chemical composition of water entering and traversing the emplacement drift used in the TSPA-VA are a significant advance. DOE should continue to document the bases for simplifications used in modeling coupled THC effects on the chemical environment for RN release.

The dissolution kinetics of the primary phase is dependent on the effective reactive surface area of SNF. DOE has not provided an adequate basis for the assumed surface area (U.S. Nuclear Regulatory Commission, 1999e).

Overall, DOE is adequately addressing dissolution rate-controlled release of RNs from SNF through experiments and modeling. However, if DOE chooses to use a more realistic intrinsic dissolution model, DOE will need to provide data and analyses to support the assumption of the chemical environments expected to exist inside WPs. In addition, DOE should provide a technical basis for its estimation of surface area in irradiated fuel pellets and an evaluation of the consistency among various test results to be used in model calculations (U.S. Nuclear Regulatory Commission, 1999e).

The solubility-limit model used by DOE was a hybrid of solubility-limit distributions determined partially by expert elicitations. The expert elicitations used to determine the distributions may not meet the programmatic acceptance criteria for expert elicitations and should be reassessed in light of NRC guidance (Kotra, et al., 1996). The solubility limits used in the TSPA-VA (U.S. Department of Energy, 1998a) also need to be reevaluated by DOE as the water chemistry inside the WP becomes better known. Finally, DOE needs to provide experimental confirmation of the solid Np compounds assumed to be in equilibrium with the dissolved Np species (U.S. Nuclear Regulatory Commission, 1999e). DOE should clearly indicate that solubility limits used in their PAs are not strict thermodynamic solubility limits (a single solid elemental compound assumed to be in equilibrium with the dissolved elemental species). DOE should indicate that the values used in their solubility model are effective release limits, based on test data.

In general, DOE is adequately addressing the effect of secondary minerals on RN release through experiments and modeling (U.S. Nuclear Regulatory Commission, 1999d). However, consistency in the assumptions of dissolution rates and retention factors for RNs must be examined further, as noted previously. The protective role of secondary minerals has not been considered in TSPA. In addition, DOE needs to consider how corrosion products from degradation of the WP and internal materials affect secondary mineral formation and retention of RNs (U.S. Nuclear Regulatory Commission, 1999e).

In the TSPA-VA (U.S. Department of Energy, 1998a), estimates of colloid formation from SNF were provided through expert elicitation. These values can be considered as bounding values. Although DOE is currently adequately addressing the processes of colloid formation in its general aspects, DOE should consider comparing their bounding values to the colloid contribution to actinide release derived from their SNF dissolution experiments (U.S. Nuclear Regulatory Commission, 1999e).

DOE did not consider all pertinent failure mechanisms of SNF cladding and does not have adequate data to fully support performance claims of cladding as an additional metallic barrier to the release of RNs (Holonich, 1999). The well-established susceptibility of Zircaloy to both pitting corrosion and SCC was not considered either mechanistically or quantitatively (U.S. Nuclear Regulatory Commission, 1999e). Hydrogen embrittlement, which could lead to an accelerated form of mechanical failure that would expose a larger fraction of the fuel surface area to the aqueous environment, was not considered. The potential for possible HE of Zircaloy cladding resulting from the effects of environments present inside breached WPs needs to be assessed (U.S. Nuclear Regulatory Commission, 1999e). The predominance of certain failure processes over others may lead to substantial variations in the surface fraction of irradiated $UO_2$ pellets exposed to the drift environment, resulting in significant uncertainties in the estimations of the dose. In addition, DOE has limited information to adequately support its estimates for the effects of cladding degradation on repository performance. Additional data and analysis of the neglected failure mechanisms will be required for a complete LA. The amount of data required for LA and the need to confirm expected performance of SNF cladding will depend on the importance of RN release rates and solubility limits to DOE’s safety case (Holonich, 1999).

DOE took credit for partially failed containers as another barrier to RN release (U.S. Department of Energy, 1998a). The effectiveness of the container materials in reducing RN release depends on the size and distribution of corrosion pits, mode of container failure, presence of through-wall cracks, and the effect of corrosion products in the pits. Although models of diffusion and convection are available to analyze restricted RN release through perforations or holes, experimental data are scarce to support the models (U.S. Nuclear Regulatory Commission, 1999e). DOE should provide adequate experimental data as a basis for the application of models of radionuclide transport (RT) through perforations both in containers and fuel cladding or demonstrate that the parameter values used bound actual conditions.

The total risk associated with internal criticality is the combination of probability and consequences for all the possible scenarios and configurations using the incremental dose to the member of the critical group at 20 km from the proposed YM site. The in-package criticality consequence analysis presented in the TSPA-VA is with respect to steady-state conditions (for 10,000 years) for a single pressurized water reactor WP. The only consequence DOE considered was the RN buildup from a long-term steady-state critical condition. The increase in the isotopes important to repository performance, I-129, Tc-99, Np-237, and U-234, is between 4 and 11 percent. DOE concluded that the consequences of an in-package criticality was small compared with the measures for nominal repository performance. Other consequences such as additional heat buildup and its effect on the WP corrosion and waste form dissolution have been considered only cursorily (U.S. Nuclear Regulatory Commission, 1999e).

The TSPA-VA presented a simplified analysis of nuclear criticality external to the WP (U.S. Department of Energy, 1998a) consistent with the methodology proposed in the topical report on disposal criticality (U.S. Department of Energy, 1998d). DOE concluded that the external criticality mechanisms are exceedingly unlikely. The near-field scenario involves transport of fissile material (U and Pu) out the bottom of a breached WP. The scenario then envisions accumulation of fissile material in the invert and rock material in the bottom of the drift via sorption or precipitation. To calculate the quantity of fissile materials that could be released from the WP, DOE uses high solubilities for U (6,000 ppm) and Pu (78 ppm), estimated for high-pH conditions, in its evaluation of the scenario. This assumption is conservative. Calculations by DOE suggest that this mechanism is incapable of resulting in mass concentrations of U and Pu sufficient for criticality for HLW glass logs. If criticality within the near field is abstracted by DOE, this abstraction would need to assess the impacts of the added thermal output on repository behavior (U.S. Nuclear Regulatory Commission, 1999d).

Contribution of the HLW glass to the source term could be significant if the rate at which the RNs can be released and transported from the glass is higher than that from the SNF (e.g., RNs released in colloidal form; U.S. Nuclear Regulatory Commission, 1999e). The contribution also could be significant if RNs contained in the hydrated layer (corrosion product layer adhering to the glass surface) are released in larger quantities as a pulse. DOE has not confirmed that, in the above-mentioned cases, RNs are not released at rates greater than the rates at which they are released from SNF. DOE should consider the effects of such processes and, hence, RN release from HLW glass in the PA. Models for glass waste form corrosion include three stages: the short-term stage when the chemical potential gradient between the glass components and the local environment is the steepest; the intermediate stage, when the corrosion rate decreases as the concentration of reaction products increases; and the long-term stage, when glass corrosion rate is further affected by the precipitation of secondary phases that exceed solubility limits at the altered zone. The last stage, the long-term stage, cannot be characterized by a single reaction rate (U.S. Nuclear Regulatory Commission, 1999e) as has been proposed currently by DOE (U.S. Department of Energy, 1998a). DOE has not taken into account different stages of the dissolution process in long-term glass dissolution models. In addition, models for matrix dissolution should cover a full range of the evolving environments that could potentially contact the WPs at the proposed YM repository. Although DOE claims to have waste form dissolution models that directly incorporate rates that depend on pH (TRW Environmental Safety Systems, Inc., 1998), the TSPA-VA analysis does not include a consideration of alkaline pH effects on glass waste dissolution. DOE should use appropriate models, tests, and analyses that are sensitive to the THC couplings under consideration for both the natural and engineering systems (U.S. Nuclear Regulatory Commission, 1999d).

The DOE treatment of the formation of secondary minerals during the corrosion of HLW glass is incomplete. The DOE models include the effect of temperature, pH, and dissolved silica; however, they do not consider the incorporation of RNs in the alteration phases that may result in periodic release spikes. If the models are simply based on experimental dissolution data for stages I or II that exhibit significant retention of RNs in the secondary phases, evaluation of the long-term RN release rates could be nonconservative (U.S. Nuclear Regulatory Commission, 1999e).

DOE has identified dominant colloid formation processes under anticipated repository conditions but has not modified the long-term dissolution models to account for such events (U.S. Nuclear Regulatory Commission, 1999e). DOE has not performed calculations to estimate the amount of colloids that can be transported through WP perforations (U.S. Nuclear Regulatory Commission, 1999e). The effect of microbes on the dissolution of natural glasses can be significant and microbes can also change the solubilities of RNs by the increased production of organic acids (U.S. Nuclear Regulatory Commission, 1999d). DOE did not attempt to evaluate potential microbial effects on RN release (U.S. Department of Energy, 1998a). DOE should use the time-history of temperature, humidity, and dripping to constrain the probability for microbial effects, such as production of organic by-products that act as complexing ligands for actinides and microbially enhanced dissolution of the HLW glass form (U.S. Nuclear Regulatory Commission, 1999d).

Transport of RN through the EBS and near-field environment, including sorption onto EBS materials, is new to DOE's TSPAs. The invert is assumed to be intact concrete, an assumption that DOE recognizes is possibly nonconservative (TRW Environmental Safety Systems, Inc., 1998). Limited data are available to support DOE's abstraction of the hydrologic and chemical characteristics of the engineered materials through which RNs are transported in the EBS (U.S. Nuclear Regulatory Commission, 1999d).

DOE's treatment of the sorptive characteristics of the engineered materials beneath the WPs has some weaknesses. Transport of RNs through the EBS is simulated using a $K_d$ to represent interaction with the invert. DOE recognizes that the sorption characteristics of the invert are poorly understood (U.S. Department of Energy, 1998a), and the sorption coefficients used in the TSPA-VA are referred to as "placeholder $K_d s$" by DOE (TRW Environmental Safety Systems, Inc., 1998).

The DOE analysis of transport through the engineered materials beneath the WP omits the potential effect of degradation of the invert and assumes that its effect on overall system performance is insignificant because of the small transport length involved relative to the total transport length (U.S. Nuclear Regulatory Commission, 1999d). DOE supported this conclusion with results of sensitivity analyses indicating that retardation in the invert has little significance to total dose. NRC staff agrees that the short transport length through the invert relative to the total transport length suggests that retardation in the invert is likely to have little effect on overall system performance of the magnitude of the dose at long time periods. However, the delay caused by transport through the invert is a substantial portion of a 10,000-year regulatory period and will need to be supported by additional data (U.S. Nuclear Regulatory Commission, 1999d).

#### 5.3.1.5 Climate and Infiltration

The discussions that follow for the DOE approach to abstracting climate and infiltration into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of climate and infiltration.

##### 5.3.1.5.1 Description of the U.S. Department of Energy Approach—Climate and Infiltration

Climate modeling was used to provide precipitation rates and water table elevations that varied as a function of future climates. Future climate was modeled in the TSPA-VA as a sequence of discrete states. Only three discrete climate states were considered for TSPA-VA: dry (present-day), long-term average (LTA), and superpluvial. Present climate represented relatively dry, interglacial conditions, while the LTA represented an average pluvial period at YM. The superpluvial represented periods of extreme wetness. The mean annual precipitation (MAP) for the present, LTA, and superpluvial were 150, 300, and 450 mm per year, respectively. Climate models strongly impact performance through their influence on precipitation and evapotranspiration. These factors, in turn, influence the predicted infiltration in the UZ flow model.

DOE's TSPA-VA (U.S. Department of Energy, 1998a) used a spatially heterogeneous infiltration map (Flint, et al., 1996) as an upper boundary condition to the site-scale UZ flow model (Bodvarsson, et al., 1997) to determine percolation at the repository horizon. Distributed net infiltration rates were determined for each of the three climate states. The infiltration model simulated water movement at the ground surface by solving water mass balances using precipitation, a model for evapotranspiration, and available water in the soil profile. Also considered were ground surface elevation, slope, bedrock geology, soil type, soil depth, and geomorphology. The primary driver for the infiltration model was precipitation, which was input using a stochastic model based on available records. Daily precipitation records were used from different locations for the infiltration model. General results of the infiltration model were (i) the modeled infiltration is highly heterogeneous and clearly correlated with topographic features, (ii) the highest net infiltration occurred along the Yucca Crest, and (iii) net infiltration was lower in the washes. The spatially distributed infiltration maps were then upscaled to the site-scale UZ flow model by averaging the simulated infiltration values over each surface element in the UZ flow model. The average infiltration rates over the repository for the present-day dry, LTA, and superpluvial climates were 7.7, 42, and 110 mm per year, respectively. A factor of three was used for the upper and lower bounds for the range of infiltrations considered in each climate scenario. This was based on a sensitivity analysis to determine the effects of episodic infiltration on the percolation at the repository horizon on a yearly basis.

For infiltration, DOE links the periodicity of MAI to glacial cycles through postulated MAP. The recent DOE model for infiltration incorporates the effects due to runoff/runon and variations in vegetation and temperature due to climate change.

#### 5.3.1.5.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Climate and Infiltration

The current infiltration over the mountain-scale model of UZ flow is calculated for each 30 × 30 m pixel. The spatial heterogeneity is primarily impacted by the variation in soil depths across the site. The map of infiltration across the site used by DOE (Flint, et al., 1996) accounts for present-day precipitation, temperature, vegetation, and soil conditions. Independent NRC calculations predict broadly similar patterns of infiltration (U.S. Nuclear Regulatory Commission, 1997c) though the magnitudes of the latter are higher by about a factor of two. Infiltration estimates based on temperature data and on chloride chemistry of the perched water may support the higher values. The VA addresses uncertainty in infiltration values by sampling three different infiltration maps: the basecase, the basecase divided by three, the basecase multiplied by three. The temporal occurrence of the basecase, lower infiltration map, and higher infiltration map are 60, 30, and 10 percent, respectively. Further support is needed for the basecase infiltration map, and emphasis on the lower infiltration map in accounting for uncertainty needs to be modified.

To account for climate changes over the 10,000 and 100,000 year modeling periods, the VA uses twice the current precipitation for the LTA and three times the current precipitation for superpluvial periods; the latter does not occur during these modeling periods. Infiltration maps are recalculated using the higher precipitation values, though temperature, vegetation, and soil conditions are not modified. It is not clear that infiltration changes caused by climatic changes can be bounded simply by changes in precipitation. In addition, surface runoff or lateral subsurface flow may be a focusing mechanism for infiltration, both for current conditions and the LTA climate, and should be incorporated into the present-day infiltration maps.

Independent modeling yielded results comparable to DOE estimates showing net infiltration over the repository footprint in the range of 6- to 12-mm per year depending on the assumed parameter values such as bedrock fracture properties, vegetation, soil depth, and slope. Contingent upon additional technical bases provided and the values that are ultimately used in the TSPA-SR, the climate and infiltration ISI is considered to be resolved. The resolution of this ISI basically means that the staff is satisfied with the DOE estimates of subarea-averaged, present-day infiltration. Remaining concerns regarding potential intra-subarea focusing of flow or transient attenuation mechanisms that might be operative under present or future climate conditions are being addressed under the ISI covering percolation and seepage.

#### 5.3.1.6 Flow Paths in the Unsaturated Zone

The discussions that follow for the DOE approach to abstracting flow paths in the UZ into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of flow paths in the UZ.

##### 5.3.1.6.1 Description of the U.S. Department of Energy Approach—Flow Paths in the Unsaturated Zone

The following approach is used in the TSPA-VA (U.S. Department of Energy, 1998a) to calculate UZ water flow at YM and seepage. MAI is used as a steady-state flux boundary condition to the dual-continuum, 3D, UZ site-scale flow model. This UZ flow model is used during the various climate and infiltration scenarios to create maps of predicted deep percolation flux at any given location of the proposed repository horizon. For the TSPA-VA analyses, the repository flux maps are divided into six repository subregions of differing area-averaged deep-percolation flux rates (U.S. Department of Energy, 1998a). The flux rates for the six subregions are then used as boundary conditions in a drift seepage model. The drift seepage model uses a single-porous-media continuum approach. In this approach, the network of intersecting fractures in the proposed repository horizon is treated as a continuous porous medium. The process-level seepage model calculates two quantities for each of the six repository subregions used in TSPA analyses: (i) the fraction of WPs that receive dripping water (seepage fraction) and (ii) the flow rate of dripping water hitting wetted packages (seep flow rate). Uncertainty is handled by obtaining model results for nine different combinations of two key model parameters—fracture permeability and fracture van Genuchten alpha value. Each of the nine combinations of these two parameters is assigned a discrete probability of occurrence, such that the nine probabilities have a sum of one. DOE assumes that results obtained from the nine parameter combinations bound the realm of possible outcomes. The resulting ranges and probability distributions for the seepage fraction and the seep flux rate are independently sampled in the DOE's TSPA code (U.S. Nuclear Regulatory Commission, 1999h).

The hydrologic properties of the 3D, mountain-scale, UZ flow model were determined using both direct measurements and calibration with field data (e.g., core samples, borehole log data, *in situ* water potential and temperature measurements, fracture measurements from the ESF, *in situ* pneumatic data, air permeability tests, and geochemistry data.) The van Genuchten/Mualem functional form was used to determine fluid pressure and relative permeability as a function of saturation and to represent the saturation and desaturation behavior of both matrix and fractures.

The UZ flow model is used to generate 3D dual-continuum flow-field maps of groundwater mass fluxes in both fracture and matrix continua. These flow-fields are then used as input to the UZ RT model, which is used to predict the mass flux of RNs to the water table. Several calibrated flow-fields are derived for a variety of assumptions regarding present-day infiltration rates, fracture-continuum properties, and fracture matrix interaction.

TSPA predictions of repository performance depend considerably on fracture-to-matrix (F/M) flux distributions (i.e., flow fields). Results presented in the TSPA-VA show that flow through the UZ was predominantly in the fractures for the welded units and predominantly in the matrix for nonwelded units. The F/M reduction factor is used to account for the fact that not all fractures are active in conducting water flow, and those that are active are typically not fully saturated. Thus the wetted contact area through which fluids can move between fractures and matrix is expected to be somewhat less than the full F/M interface area. Hence, a reduction factor is used. For the calibrated UZ flow model used in the TSPA-VA basecase analyses, the F/M coupling factor was used solely as a calibration parameter to match model results to observed matrix saturation values. In the sensitivity analyses, DOE used F/M coupling factors that were set equal to the upstream relative permeability (a function of fracture saturation).

The $\alpha_f$ parameter is one of several parameters developed by van Genuchten (1980) to describe the relationship between saturation and capillary pressure in a porous medium. When considering mass flux between fractures and matrix, it is the differences in capillary pressure between the two that drive transfer of fluid between the continua. The $\alpha_f$ value is important because, for any given saturation level, the assumed $\alpha_f$ value affects how strongly a fracture retains the water that resides within it. Of course, the assumed value for matrix $\alpha_m$ is equally important for the same reason; however, there are numerous laboratory measurements from which to estimate $\alpha_m$, whereas there is little basis for estimating $\alpha_f$ values. In the DOE UZ flow model, $\alpha_f$ is little more than a calibration parameter, which, like the F/M coupling factor, is used to match model results to observed matrix saturation values.

A multiscale modeling approach was used to abstract thermal hydrology processes into the TSPA-VA. The multiscale approach combines 1D, 2D, and 3D drift-scale thermal models and TH models with the UZ 3D-flow model. These models were used in the TSPA-VA to estimate WP corrosion rates, waste-form dissolution rates, and transport of RNs through the EBS. Four different models were used in the TH multiscale modeling and abstraction method—SMT, SDT, LDTH, and DDT, where S is smeared heat source, M is mountain scale, the first D is drift scale, T is heat flow by conduction, TH is thermal-hydrological coupling, L is line loading, and the second D is discrete heat source. Major assumptions in the multiscale modeling are:

- Perched water is omitted
- Small-scale and lateral heterogeneity are omitted from the TH calculations

- Bulk permeabilities assigned to an open drift range from $10^{-12}$ to $10^{-18}$ $m^2$
- Pressurization within the drift does not occur
- THM and THC alterations of hydrological properties can be neglected for the basecase

A relatively simplified representation of the near-field chemistry was presented in the TSPA-VA. A key assumption is that mechanical and chemical changes do not alter hydrologic properties. The response of the mountain-scale UZ flow model to the effects of the chemical and mechanical changes to fracture properties was not coupled in the TSPA-VA. Simplifications that relate TM and TC influences into a UZ TH simulation were proposed as a series of sensitivity studies.

Repository heating is assumed to have a significant effect on seepage in the TSPA-VA. To apply the seepage abstraction to a TH calculation, the DOE used a generalized equivalent continuum model with mean infiltration and nominal fracture van Genuchten alpha, for repository center locations. However, seepage was reduced to zero for the period of time that the temperature of the drift-wall above the WP exceeded boiling (TRW Environmental Safety Systems, Inc., 1998). THM and THC alterations of hydrological properties were neglected for the basecase (U.S. Nuclear Regulatory Commission, 1999j).

#### 5.3.1.6.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Flow Paths in the Unsaturated Zone

The mountain-scale UZ flow model is used to translate infiltration to estimates of percolation flux at the repository horizon. Because it is difficult to obtain direct measurements of the model parameters, the model is calibrated through a process of constraining parameter ranges in a model inversion process. The large number of unknown parameters has led to a problem in nonuniqueness for the data sets. There are approximately 150 parameters to estimate and 300 saturation values to match. As a result of the uncertainty in the estimation of the hydraulic parameters, numerous parameter sets have been produced from the inversion process for the UZ flow model. Improved basis for the parameter ranges used in the model would significantly improve the confidence in the calibrated parameter sets.

There are measurement uncertainties for all of the parameters. Scaling issues imply that the laboratory measured matrix permeabilities are lower than field scale values applicable to the cell sizes used in the flow model; this is especially true for the nonwelded units. The laboratory measurements may give a good indication of heterogeneity or relative variations, but not absolute magnitudes for the nonwelded units. Fracture properties were estimated from air permeability and pneumatic response measurements. However, *in situ* air permeability for the fracture system may not be representative of the UZ water pathway permeability. UZ constitutive relationships for the fracture continua have not been measured; they only have been inferred from fracture characteristics or arbitrarily constrained. The fracture characteristics used to support estimates of hydraulic properties were themselves biased. Effects due to (i) undersampling of small fractures; (ii) biased orientation in the ESF detailed line survey [no Terzaghi corrections were made (Terzaghi, 1965)]; and (iii) poor characterization of aperture distributions not addressed in the estimation of hydraulic properties using fracture properties. The matrix/fracture interaction term is entirely a calibration parameter because there was no supporting measurement or indirect calculation. Fault zones were explicitly incorporated into the model as separate elements. However, the effect of faults on UZ flow is not understood. Faults may act as barriers or conduits, and their properties may readily change along a fault plane.

Episodic flow is thought to be dampened by the PTn. However, abundant geochemical data suggest there are fast pathways bypassing the PTn. The most prominent data are the bomb pulse $^{36}Cl$ data at the repository horizon and the young, dilute water in the perched zone. Fast-path contributions to flow, as suggested by geochemical data, are not adequately represented in the site-scale model.

The DOE is collecting field data and conducting workshops to justify the fracture versus matrix flow used in the TSPA-VA. Results presented in the TSPA-VA show that the flow through the UZ was predominantly in the fracture for the welded units and predominantly in the matrix for the nonwelded units. High infiltration resulting from climate change significantly increased the percolation flux in the vicinity of the repository and decreased the travel time between the repository and the water table. Travel times between the repository and the water table ranged from several days to hundreds of thousands of years. The fastest transit times resulted from flow through fractures, whereas the matrix contributed to particle breakthrough at the water table at significantly longer times.

The values assigned to fracture continuum hydraulic properties in the TSPA-VA parameter sets are not justified by the distribution of fracture apertures seen on the model grid scale (U.S. Nuclear Regulatory Commission, 1999h). DOE estimates of fracture alpha values are based on estimates of “effective fracture aperture” obtained from air permeability studies in the ESF. It is difficult to draw a simple relationship between fracture aperture and fracture alpha values. Even if such a relationship held true, the values calculated for fracture-alpha should be related to the largest aperture sizes encountered on the model grid-block scale (U.S. Nuclear Regulatory Commission, 1999h). Similarly, values assigned to the fracture *m*-parameter should be related to the range and distribution of aperture sizes from narrowest to widest.

Few data are available from which to estimate hydraulic properties of fractures in the rock units above and below the proposed repository horizon. Additionally, the fracture frequency data collected in the ESF at YM may be biased because scanline sampling of fractures results in undersampling fractures that are subparallel to the scanline (Winterle, et al., 1999, Chapter 2). Thus, fracture frequency in the ESF may be significantly greater than presently estimated. Because these fracture frequency data are used in conjunction with air permeability tests to estimate fracture-alpha ($\rho_F$) values used in the TSPA-VA analyses, the estimated range of $\rho_F$ values may be too high. Higher values of $\rho_F$ result in less water flowing in fractures; thus, TSPA-VA analyses may be overly optimistic in the predicted fraction of water flowing in rock matrix.

Although more is known about rock matrix properties, considerable uncertainties still exist. For example, preliminary data emerging from measurements in the East–West Cross Drift at YM appear to indicate matric potentials (capillary pressures) are higher than expected based on laboratory-determined capillary pressure-saturation relationships; hence, *in situ* matrix saturations are likely greater than those estimated from rock-core samples. Despite the uncertainty in the parameter values assigned to the rock matrix, the basecase UZ flow-fields that are used in the TSPA-VA analyses to account for uncertainty all appear to use the same set of rock matrix hydraulic properties (TRW Environmental Safety Systems, Inc., 1998, Tables 2-21 through 2-23).

TSPA predictions of repository performance have been shown to be sensitive to F/M flux distributions (also referred to as flow-fields). It is important to consider a set of possible distributions that bounds the uncertainty in UZ fracture and rock matrix hydraulic properties.

Conversely, the limited set of flow-fields used in the TSPA-VA basecase and sensitivity analyses (U.S. Department of Energy, 1998a, Volume 3) does not adequately bound this uncertainty, so the expected benefits of water flowing through rock matrix may be overly optimistic.

To account for parameter uncertainty in TSPA-VA analyses, alternative model scenarios were developed using estimated minimum, mean, and maximum $\alpha_f$ values. Each of the alternative model scenarios was calibrated to match matrix saturations determined from rock-core samples by adjusting the value of an F/M interaction factor used to limit the modeled exchange of water between fracture and matrix domains. Because matrix properties remain unchanged for each scenario and each model scenario is calibrated to the same observed saturations, the amount of flow in the rock matrix remains unchanged; hence, the flow traveling in fractures also remains unchanged. As a result of this calibration approach, the UZ flow-fields used in the TSPA-VA do not reasonably bound the combined uncertainty in rock matrix and fracture hydraulic properties.

In the TSPA-VA analyses, it appears that greater than 70 percent of mass flux in the UZ can be significantly delayed en route to the water table due to flow in the rock matrix. However, given the uncertainty in rock matrix and fracture hydraulic parameters, it is quite possible that a significantly lower fraction of water participates in matrix flow. As matrix flow is the only effective natural barrier between the repository and the water table, it is important that TSPA analyses reasonably bound the likely distribution of flow between fractures and matrix. Where irreducible uncertainties exist, model assumptions should favor fracture flow.

Although this concern is presently unresolved, ongoing and planned site characterization, field testing, and modeling described in DOE's LA Plan and Costs (U.S. Department of Energy, 1998a, Volume 4) may result in resolution of this concern. For example, DOE is analyzing the effects of heterogeneity on the flow paths in the UZ flow and transport in the variably saturated Calico Hills nonwelded unit at the Busted Butte test facility and via niche and alcove studies in the ESF. At a UZ Flow and Transport Workshop held at Sandia National Laboratories (SNL) (December 14–16, 1998, Albuquerque, New Mexico), DOE researchers addressed the limitations of the F/M interaction factor and proposed:

- Use of an active fracture model (Liu, et al., 1998) in which the fraction of the active fractures are assumed to be a power function of the effective liquid saturation

- Improvement of the conceptual models for F/M interaction and perched water

- Validation of models through continued analysis of site data and data from analog sites

- Evaluation of the appropriate range of parameters, given the nonunique flow-fields obtained from inverse model calibration methods

The DOE drift-scale, process-level seepage model, used to calculate seepage fraction and seep flow rate for TSPA, does not include several potentially important processes and has not been shown to yield reasonably conservative upper bounding values. Review of the DOE drift seepage approach has identified inadequacies in the data, experiments used to collect the data, the models used to describe the seepage process, and the methods used to abstract seepage into PAs (Hughson, 1999; Drift Seepage Peer Review Panel, 1999; U.S. Nuclear Regulatory Commission, 1999h,j,m).

Many physical properties of repository drifts are not considered in the seepage model (U.S. Nuclear Regulatory Commission, 1999h,j). Heterogeneity in the hydraulic properties of the rock that surrounds drift openings may be the single most important factor affecting water flux into open drifts, yet the DOE seepage model does not account for the multiple scales at which heterogeneity occurs (U.S. Nuclear Regulatory Commission, 1999h; Drift Seepage Peer Review, 1999). On the very small scale of a drift wall, the presence of surface irregularities and conducting fractures that dead-end at the drift crown will result in less capillarity and thus less diversion of percolation flux around the drift (Hughson, 1999). These features were not accounted for by the DOE (U.S. Nuclear Regulatory Commission, 1999h).

Not considered in the DOE seepage model is that the geometry of the drifts is likely to change due to rockfall (U.S. Nuclear Regulatory Commission, 1999g,h). Drift collapse may also significantly alter effective parameters describing moisture retention characteristics of the fracture continuum and thus result in more seepage for a given percolation flux (Holonich, 1999; Drift Seepage Peer Review Panel, 1999).

An additional concern is that the seepage model does not consider the importance of transient (episodic) infiltration (U.S. Nuclear Regulatory Commission, 1999h). Episodic infiltration could be important at early times due to potential penetration of the boiling isotherm. At later times, sequential transient episodes can cause more water to enter the drift than at either steady state or during a single transient pulse. As a result of these uncertainties, the quantity of water that would enter the emplacement drifts may be significantly underestimated (U.S. Nuclear Regulatory Commission, 1999h). Additional data and analysis of seepage under both isothermal and thermal conditions will be required for a complete LA (U.S. Nuclear Regulatory Commission, 1999a).

Based on descriptions provided in the TBD VA (U.S. Department of Energy, 1998a), the DOE multiscale TH model appears an acceptable systematic analysis of thermal effects on flow (TEF) at the proposed YM repository. Insufficient detail is included in the TBD VA to fully understand the complete TEF abstraction process. Based on the TEF IRSR analysis, there are components to the multiscale TH model that require modification or enhancement. The more important of these modifications or enhancements consist of

- The inclusion of sufficient heterogeneity in media representation in models to avoid masking or omitting performance affecting heat and mass transfer mechanisms such as seepage and focused flow

- The inclusion of TH processes on seepage for the entire repository performance period (TH driven flow cannot be neglected for the initial 5,000 years after waste emplacement)

- The inclusion of penetration of the boiling isotherm by flow down a fracture. The assumption that water will not contact the WP until the WP temperature decreases below boiling is not conservative

Coupled THC processes that effect flow were not considered explicitly in the TSPA-VA. These processes (dehydration of zeolitic horizons, coupled THC processes that affect the porosity and permeability of the natural system, and coupled THC processes that occur at the interface of the natural system and the engineered components) need to be considered in the model abstractions. Although DOE did not abstract the effects of coupled THC processes on flow in the TSPA-VA, they appear to be planning to address this topic in future TSPAs.

### 5.3.1.7 Radionuclide Transport in the Unsaturated Zone

The discussions that follow for the DOE approach to abstracting radionuclide transport in the UZ into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of radionuclide transport in the UZ.

#### 5.3.1.7.1 Description of the U.S. Department of Energy Approach—Radionuclide Transport in the Unsaturated Zone

For the UZ, the DOE TSPA VA recognizes important factors from previous TSPAs affecting flow and transport: (i) the UZ percolation rate; (ii) the partitioning of flow between matrix and fractures; and (iii) the sorption coefficients. In the current DOE approach, flow and transport are decoupled. A library of steady-state flow fields generated for various infiltration rates reflects uncertainties in hydrologic properties of the different stratigraphic units in the UZ. For each realization, a new flow-field is selected and transport is simulated by using the FEHM particle tracker module. FEHM uses a dual permeability formulation representing interacting fractures and matrix continua throughout the UZ. Transport processes considered include: (i) advective and diffusive exchange between fractures and matrix; (ii) sorption/desorption; (iii) birth and death of colloids; and (iv) colloid filtration.

Nine RNs ($^{14}C$, $^{99}Tc$, $^{129}I$, $^{79}Se$, $^{231}Pa$, $^{234}U$, $^{237}Np$, $^{239}Pu$, and $^{242}Pu$) were tracked from the EBS through the UZ. In the DOE VA (U.S. Department of Energy, 1998a) and the TSPA-VA (TRW Environmental Safety Systems, Inc., 1998, Chapters 7 and 8), these RNs are assumed to interact with the geologic setting only in the case of transport through the matrix in the fractured tuff of the UZ. Due to lack of information on fracture mineralogy and relatively rapid travel times, it is assumed that there is no retardation (i.e., $K_d = 0$) in fractures for all nine RNs being tracked in PA. Sorption coefficients in the matrix were assigned probability distributions based on expert elicitations conducted for earlier TSPA efforts.

The DOE performed sensitivity analyses using the TSPA-VA code to investigate the effects of uncertainty in sorption parameters on performance. Based on the current design, DOE sensitivity analyses indicate that repository performance is not affected strongly by uncertainty in matrix sorption for transport through the UZ.

Colloid transport was included for the first time in the TSPA-VA. DOE recognizes that the transport velocity of RNs attached to colloids may be faster than that of dissolved RNs because colloids may travel in the faster parts of the flow paths, and colloids may sorb to host rock less strongly than dissolved RNs. For example, DOE notes that under certain conditions, colloid-facilitated transport is moderately important to repository performance in the time period from 10,000 to 100,000 years. Only plutonium was considered in the analysis of RT by colloids. Plutonium is believed by DOE to be the RN most likely affected by colloidal transport because it is a major part of the waste inventory, has low solubility, and high sorption onto host rock. Field evidence at the NTS also supports the rapid migration of plutonium with a colloid phase (Thompson, 1998; Kersting, et al., 1999). Colloid transport of plutonium is modeled with an effective retardation factor, using the expression

$$(R_f) = \frac{R_f + K_c R_c}{1 + K_c}$$

where $R_f$ is the retardation of aqueous plutonium, $R_c$ is the colloid filtration factor ($R_c$ = 1 for the no-filtration case) and $K_c$ is the unitless colloid partitioning coefficient such that

$$K_c = K_{dcol} \times C_{col}$$

where $K_{dcol}$ is the plutonium sorption coefficient on the colloid phase and $C_{col}$ is the concentration of colloids in the groundwater. For reversible sorption on colloids, a log-uniform distribution of $K_c$ is assumed in the TSPA-VA, with a maximum of 10 and a minimum of $10^{-5}$. In addition, the ratio of irreversibly sorbed plutonium colloids to reversibly sorbed plutonium colloids is modeled assuming a range of $10^{-10}$ to $10^{-4}$, based on observations of the Benham blast site on the NTS (Thompson, 1998; Kersting, et al., 1999). In the far field, this irreversibly sorbed plutonium is treated as a nonsorbing, slowly diffusing contaminant (U.S. Department of Energy, 1998a, Volume 3, Section 3.5.2.4).

In the basecase presented in the TSPA-VA, the major contributors to peak dose rate at 10,000 years are calculated to be the high-solubility, nonretarded RNs $^{99}$Tc, $^{129}$I, and $^{14}$C. Other RNs do not become significant contributors to dose until later times of 50,000 years or more. These include the poorly sorbed RN $^{237}$Np. At 100,000 years, $^{99}$Tc, $^{237}$Np, and $^{129}$I are the major contributors to peak dose rate. Colloidal contributions to dose also begin to become significant at times of about 100,000 years or more. In the basecase, $^{239}$Pu breakthrough at 20 km occurs at about 1,500 years due to rapidly transported, irreversible plutonium colloids. Early plutonium concentration is dominated by irreversible colloids up to about 50,000 years where the amount of plutonium reversibly bound to colloids begins to dominate. At 100,000 years, About 2 percent of the peak dose rate is colloidal plutonium (mostly $^{239}$Pu). At 1,000,000 years, $^{237}$Np contributes the most to dose, but plutonium (mostly $^{242}$Pu) is about 8 percent of the peak dose rate (U.S. Department of Energy, 1998a, Volume 3, Section 4.3.1.1).

#### 5.3.1.7.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Radionuclide Transport in the Unsaturated Zone

The UZ at YM is composed of porous rock and fractured rock that constitutes the RN pathway from the repository to the SZ. Most of the YM geochemical work in the past 20 years has been directed toward determining the retardation of RNs in porous rock. Significant progress has been made to address this issue (one of the subissues of the Radionuclide Transport Issue Resolution Status Report, Revision 1) that is important to waste isolation and repository performance. However, in that time, there have been major changes in the conceptualization of the geologic setting of the repository that affect the relative importance of RT through porous rock in the UZ on performance. Major changes include the recognition that average infiltration is one or two orders of magnitude greater than original estimates and the consideration of the point of compliance up to 20 km away from the repository. The greater average infiltration results in a greater proportion of the flux bypassing the sorptive porous rock by flow in fractures. A 20 km point of compliance would result in the need to consider the alluvium along with porous and fractured rock. These major changes reduce the relative importance in PA of RT in porous rock of the UZ.

Many important effects may need to be considered when abstracting RT in the UZ. These include effects related to physical transport such as: (i) the use of appropriate conceptual models for F/M interactions; and (ii) the range and dependencies of parameters associated with (a) those interactions, (b) the effects of both long- and short-term transient flow conditions, and (c) the extent of lateral and longitudinal dispersion. Important considerations related to chemical interactions include: (i) the appropriateness of the minimum $K_d$ approach; (ii) the amount of sorption to be expected in fractures; and (iii) the contribution of colloids to RN flux. Finally, potentially important effects related to heterogeneities in the UZ include: (i) consideration of spatial distribution of infiltration; (ii) areal variations in amounts and compositions of zeolites; and (iii) appropriate scale of heterogeneities.

The NRC staff finds that the approach adopted by the DOE (Triay, et al., 1992) to validate $K_d$ values from batch sorption tests is logical and defensible (U.S. Nuclear Regulatory Commission, 1999c). By performing batch sorption tests using site-specific materials, followed by confirmatory tests to establish the validity of the assumptions needed for the constant $K_d$ approach, and then selecting the minimum $K_d$ from all the tests, an acceptable value can be obtained.

Overall, the NRC staff considers that the subissue dealing with RT through porous rock in the UZ has been resolved for certain RNs but not for others. Some of the RNs for which the subissue has not been resolved on the staff level may be important to performance. Three RNs are chosen as examples to highlight successes and areas needing further work. They are neptunium, plutonium, and uranium. The minimum $K_d$ approach has worked well for neptunium. The staff recognizes that multiple tests have been performed to establish reasonable $K_d$ values for this RN. Consequently, this subissue is resolved for neptunium. On the other hand, although both batch sorption tests and flow-through column tests have been performed to determine a minimum $K_d$ for plutonium, significant inconsistencies have been observed. The NRC staff recognizes plutonium as problematic and encourages further work to establish defensible $K_d$ values. For uranium, geochemical modeling suggests that a uranyl silicate phase, soddyite, could precipitate from solution, given the initial groundwater composition. Eliminating the possibility that processes other than sorption may be contributing to the removal of a RN from solution is necessary for establishing a valid $K_d$. On the other hand, the thermodynamic (geochemical) modeling could be in error based on parameter uncertainties. To date, it does not appear that flow-through column tests were performed with uranium. Consequently, this subissue has not been resolved at the staff level.

With regard to RT through fractured rock in the UZ, current PA calculations (U.S. Nuclear Regulatory Commission, 1999h,k; U.S. Department of Energy, 1998a), assume no retardation in fractures, and RNs are transported through the fractures at the same velocity as groundwater. Under these conditions, flow issues related to F/M interaction and fracture flow velocity are the critical aspects of RT. These flow issues are considered as part of the USFIC KTI (U.S. Nuclear Regulatory Commission, 1999h).

However, transport experiments have been performed using fractured rock (Triay, et al., 1997). Whereas the retardation factor in fractures is typically assumed to be 1 (i.e., no sorption) in PAs, due to the uncertainty with regard to RT in fractured rock, preliminary experiments suggest that some retardation occurs. For example, neptunium experiments have been performed and show reduced recovery and a delay in the breakthrough relative to tritium and technetium. Field scale experiments (30–100 m) conducted at the C-Wells complex (Reimus and Turin, 1997; Reimus, et al., 1998) result in bimodal breakthrough curves for nonreactive tracers (polyfluorinated benzoic acids, bromide), reactive solutes (lithium), and microspheres. Reimus, et al. (1998) suggest that fast pathways and diffusion from the fracture into the matrix may play a role in SZ transport (Reimus, et al., 1998). Matrix diffusion in the UZ has yet to be demonstrated. However, resolution of this subissue will depend on a combination of laboratory experiments by DOE and additional tracer tests like those at Busted Butte (Bussod and Turin, 1999) field site.

#### 5.3.1.8 Flow Paths in the Saturated Zone

The discussions that follow for the DOE approach to abstracting flow paths in the SZ into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of flow paths in the SZ.

##### 5.3.1.8.1 Description of the U.S. Department of Energy Approach—Flow Paths in the Saturated Zone

The TSPA 3D SZ flow model was developed using FEHMN with a model domain of about 20 × 36 km to a depth of 950 m below the water table (TRW Environmental Safety Systems, Inc., 1998). The model domain was discretized into a uniform orthogonal mesh with 500 × 500 × 50-m elements. The model was based on a refined hydrogeologic framework model used by D'Agnese, et al. (1997). Sixteen hydrogeologic units were represented as homogeneous and isotropic. Large and moderate hydraulic gradients were represented by three linear vertical features with low permeability. SZ flow was modeled as steady state. Focused recharge along the Fortymile Wash was included as specified flux, and specified pressure boundaries were applied to the lateral boundaries. A no-flow boundary was assigned to the bottom of the model domain. Model simulations were performed with isothermal conditions and uniform permeability for each hydrogeologic layer.

Trial and error calibration was performed to compare simulated hydraulic heads with observed hydraulic heads. In general, there was good agreement between simulated and observed head and the largest head residual was about 2 m along the potential flow paths downgradient of the repository. The simulated direction of groundwater flow was also consistent with the conceptual model of the SZ as suggested by regional- and site-scale flow modeling. Solute transport simulations indicated an average simulated flux of 0.61 m per year along the flow path. A particle tracking simulation was used to estimate the flow path lengths in the SZ through each of the hydrogeologic units downstream from the repository. The resultant flow was mostly in the four hydrogeologic units: upper volcanic aquifer, middle volcanic aquifer, middle volcanic confining units, and alluvium/undifferentiated valley fill. Streamtubes generated by particle tracking simulations were then used for the 1D transport simulations.

The TSPA 1D transport model developed to generate the RN concentration breakthrough curves for the TSPA-VA analyses was FEHMN. The 1D approach eliminated the transverse dispersion inherent in the previously used 3D approach due to coarse gridding. Longitudinal and transverse dispersion was included in the model as a post processing step in the form of a dilution factor. Flow and transport occurred in the six 20-km long streamtubes that are about 3000 m in width and 10–20 m in depth (width). The volumetric flow rate of each streamtube was determined at the water table from the UZ site-scale model (Bodvarsson and Bandurraga, 1997). Specific discharge into each streamtube was 0.6 m per year under current climatic conditions. The cross sectional area of each streamtube was proportional to the volumetric groundwater flow rate. Transport simulations were performed with a 5-m grid spacing in the streamtubes and a steady, unit RN mass-source at the upstream end of the streamtube. A total of nine RNs were simulated separately.

A convolution integral method, assuming linear system behavior and a steady-state flow system, was used to determine the RN concentrations in the SZ at the receptor location. This method provides an approximation of the transient RN concentration at a specific point downgradient in the SZ in response to the transient RN mass flux from transport in the UZ (TRW Environmental Safety Systems, Inc., 1998). This computationally efficient method makes full use of a single detailed transport realization for all subsequent TSPA-VA realizations. The inputs to the convolution integral approach include a unit concentration breakthrough curve in response to a step-function mass flux source (as simulated by the SZ flow and transport model) and the RN mass flux history (as simulated by the UZ transport model) (TRW Environmental Safety Systems, Inc., 1998). The effects of varying climatic conditions on RT were incorporated in the convolution integral simulations by varying the magnitude of groundwater flux and assuming there is an instantaneous change from one steady state to another due to climate change scenarios. The multi-climate convolution code was verified against a 3D SZ transport simulation using FEMHN and resulted in reasonably good agreement.

Fracturing at YM has been the subject of numerous focused investigations. DOE performed geologic mapping studies at scales of 1:2,400 to 1:24,000. Faults with 5 m or more of offset were recorded in 1:24,000 scale studies, while faults with 1 m or more of offset were recorded in the more detailed studies (U.S. Department of Energy, 1998a). Many of these studies have recently been integrated and summarized in the DOE YM Site Description (U.S. Department of Energy, 1998a): mapping and observation of natural and cleared surface exposures, examination of borehole cores, television logs, interpretation of borehole geophysical logs, and full periphery geologic mapping and scanline surveys within the ESF.

#### 5.3.1.8.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Flow Paths in the Saturated Zone

TSPAs previously conducted by the NRC and DOE differed greatly in the amount of credit taken for mixing and volumetric flow in the SZ beneath the repository (i.e., dilution). Dilution of RN releases from the repository will occur along the saturated flow path. RN concentrations decrease due to dispersion transverse to the flow path. The TSPA-95 (CRWMS M&O, 1995b) evaluation of dilution in the SZ relied on largely unsupported values for vertical mixing (i.e., mixing depths up to 2.9 km). Other analyses (Baca, et al., 1996; Kessler and McGuire, 1996) that made less optimistic assumptions affecting vertical mixing resulted in correspondingly less dilution. Estimates of RN concentrations need to be consistent with values used to estimate concentrations at the wellhead (see Section 4.3.3.1.1). Depending on water withdrawal rates for receptor groups, it could be appropriate to assume that all RNs released to the SZ are available to be captured by a well at the compliance point after migration through the SZ (amount of RNs captured by a well depends on vertical and lateral extent of RNs in the production zone and pumping rate). Based on this assumption, RN concentrations could be estimated by considering dilution through groundwater flow in the UZ, SZ, and the volume of water pumped by the well. Although the mixing effect induced by pumping diminishes the need to precisely estimate concentrations at a given point within the aquifer, determination of the vertical and lateral extent of the RN distribution within the aquifer will affect the amount of RNs intercepted by a particular well.

Analyses performed in the TSPA-VA use a dilution factor along the SZ flow path that is orders of magnitude smaller than the one used previously. The dilution factor distribution, developed by the SZ expert elicitation panel members, used in the TSPA-VA was a range from 1 to 100 with a median value of 10. The DOE has also implemented a simplified SZ transport model that consists of six streamtubes from which convolution integrals or transfer functions are developed. While longitudinal dispersion is incorporated into the transfer functions, the effects of transverse dispersion are accounted for in a dilution factor, which is applied to resident aquifer RN concentrations at the receptor location.

The NRC staff has the following technical concerns regarding the site-scale flow and transport model and the TSPA-VA approach to SZ flow and transport:

- The boundary conditions for the site-scale flow model, both flux and specified head, are not reasonably bounded as the regional flow model is not sufficiently calibrated. No vertical flow was simulated as the no flow boundary was imposed for the bottom of the model.

- The site-scale model was not sufficiently calibrated as the paucity of data prevented estimation of all parameters. The large data gap in the hydrogeologic framework model south of YM still exists.

- The horizontal spatial resolution is not sufficiently fine to include flow channelization and permeability contrasts.

- The TSPA-VA flow and transport simulations, performed using a 3D flow model and 1D transport model, assume the system is isotropic and homogeneous. There is ample evidence to suggest the presence of anisotropy and heterogeneity.

- The applicability of the dilution factor approach to sufficiently incorporate the effects of transverse dispersivity is not clearly supported by the analyses.

- The sensitivity analyses performed in the TSPA-VA did not show any sensitivity of dose to the SZ flow and transport parameters.

The following modifications or enhancement are needed for the DOE approach for modeling flow paths in the SZ:

- The regional flow model should be refined for a better estimate of boundary conditions for the site-scale flow model. Vertical flow from the deeper aquifer should be incorporated in the site-scale flow model or a technical justification for the exclusion of vertical flow provided.

- The hydrogeologic framework model used for the site-scale flow and transport model should be modified to incorporate more site-specific information south of YM. Additional field investigations and characterization are needed to address the issues of structural control on flow, flow channelization, and transition of the water table from tuff aquifer to alluvial aquifer.

- The spatial horizontal resolution of the site-scale flow model should be refined to better represent the heterogeneity in the system.

- The TSPA-VA transport simulations should consider a conceptual model that includes an anisotropic and heterogeneous representation of the SZ.

- The dilution factor approach should be either modified or supported by rigorous analyses.

- The model abstraction for SZ flow and transport should be refined so that it responds to various SZ flow and transport parameters during sensitivity and uncertainty analyses.

Information gleaned from the recent technical exchanges with the DOE indicates that a new SZFT model will be used for performing TSPA LA analyses. The fully 3D groundwater flow model will be coupled with a transport model based on random walk particle tracking method. This approach provides an improvement over the streamtube flow and transport model.

Staff have the following additional concerns about DOE analysis of SZ flow paths pertaining to sampling biases and structural controls on aquifer anisotropy. It should be noted that many of these concerns are being addressed actively in the new SZ flow model being developed by DOE.

*Sampling Biases*: Characterization of fracture networks at YM, including fault-damage zones, is impaired by several important sampling biases common to fracture analyses. If left uncorrected, these sampling biases lead to under representation of fracture intensity, porosity, permeability, and connectivity.

First, the lengths of the longest fractures in a population are often unconstrained because the ends of the fracture are obscured (blind). This bias can lead to underestimation of fracture connectivity.

Second, the orientation of a 1D sampling line (e.g., borehole or detailed line survey scanline) or 2D sampling surface (e.g., pavement, roadcut) inherently biases sampling against discontinuities parallel to the sampling line or surface and favors sampling discontinuities at a high angle to the sampling line or surface. Mathematical corrections can partially compensate for this sampling bias.

Third, because measuring every fracture from micro-scale to mega-scale is impractical or impossible for large sample areas, fracture studies usually have a size (e.g., length) cutoff. Fractures smaller than a given dimension are not counted. Consequently, small fractures are underrepresented in fracture characterization. Exclusion of small fractures could lead to an underestimation of hydrologic properties such as porosity, permeability, and fracture connectivity in these units. Elimination of fractures less than 1 m also may modify fracture intensity interpretations near faults such as the Ghost Dance fault in the ESF, where the 1 m cutoff for trace length leads to extremely variable fracture intensity estimates over a wide zone (Sweetkind, et al., 1997a,b).

While the general importance of fracture geometric and mechanical characteristics and distributions to the analyses of groundwater flow is recognized, sensitivity of such characteristics and distributions to dose still has not been quantitatively demonstrated. The staff has found, however, potential inadequacies or insufficiencies in particular DOE fracture data, distributions, and abstractions used in the TSPA-VA. Although many SZ flow modeling efforts have assumed homogeneous and isotropic permeability properties for aquifer strata, a mounting body of evidence indicates that aquifer permeability is strongly controlled by fault zones and fractures

(Ferrill, et al., 1999). Tectonic and structural features, such as fractures and fault zones, may exert a principal control on permeability and, therefore, groundwater flow. These effects occur over a large range of scale of observation, from tens of square meters to thousands of square kilometers, and include:

- At the regional-scale (thousands of square kilometers), groundwater flow in the YMR flows from an area of recharge in higher altitude areas north of YM, to lower elevation areas of discharge in Amargosa Valley and ultimately the Death Valley pull-apart basin.

- At the subregional-scale (tens to hundreds of square kilometers), large faults control the overall structural framework of YM and produce offset and tilting of aquifer strata and juxtapose different strata, allowing fluid communication between hydrostratigraphic layers. In some cases, faults may provide preferred pathways for groundwater flow. Furthermore, within strata in the YM area, fault zones and fractures produce the primary aquifer permeability. Fault and fracture permeability at the subregional-scale can be addressed by dividing the subregion into domains represented by different permeability/conductivity tensors; some domains may represent specific fault zones.

- At the local-scale (hundreds of square meters up to several square kilometers), individual faults and fracture swarms may dominate permeability or be fast flow paths, and intervening blocks of less fractured rock can be approximated by separate permeability tensors.

Staff review of fracture data and fracture data summaries indicates that the DOE's characterization of the 3D variability of abstracted fracture characteristics and distributions may not be adequate. The following observations support the conclusion:

- Fracture aperture distribution is underconstrained
- Fracture connectivity across stratal boundaries is underconstrained
- Fracture characterization in key stratigraphic units in the UZ is inadequate
- Fracture orientation (strike and dip) and lengths are not corrected for sampling bias
- Role of fracture dynamics is underemphasized
- Boundary conditions of numerical abstractions of fracture data and fracture models under ambient and thermally perturbed conditions have not been presented
- Downward convergent connected fracture networks are underconstrained
- Fault- and fracture-zone properties are underconstrained
- Nonrepresentative data sets are used as the basis for abstractions
- The assumption of isotropic fracture permeability in the SZ is unsupported and nonconservative

#### 5.3.1.9 Radionuclide Transport in the Saturated Zone

The discussions that follow for the DOE approach to abstracting radionuclide transport in the SZ into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of radionuclide transport in the SZ.

### 5.3.1.9.1 Description of the U.S. Department of Energy Approach—Radionuclide Transport in the Saturated Zone

For the SZ, simulations use 3D steady-state flow modeling with an equivalent continuum and effective transport porosity. A convolution integral approach is used to pass the RNs from the UZ to the SZ to give a concentration history at 20 km. There are six subregions at the foot of the repository at the water table where RNs enter the SZ flowtubes. The effects of climate change on flow and transport are determined, but these changes are assumed to be instantaneous step functions. Issues related to SZ flow and transport have been identified by the DOE. For example, it is recognized that channelization of flow in the SZ could increase effective flow velocity and reduce dispersivity, matrix diffusion and retardation. Also, the hydraulic characteristics of faults are uncertain. Sensitivity studies are to be performed to test the effect of faults on performance. Other issues to be addressed are colloidal transport, dispersivity, matrix and fracture sorption, possibility of vertical flow and its effect on dilution, the effect of the chemical plume from the heated repository on the SZ flow and transport, and consideration for pumping scenarios.

Nine RNs ($^{14}C$, $^{99}Tc$, $^{129}I$, $^{79}Se$, $^{231}Pa$, $^{234}U$, $^{237}Np$, $^{239}Pu$, and $^{242}Pu$) were tracked through the SZ to a receptor location at 20 kilometers. In the DOE VA (U.S. Department of Energy, 1998a) and the TSPA-VA (TRW Environmental Safety Systems, Inc., 1998, Chapters 7 and 8), these RNs are assumed to interact with the geologic setting only in the case of transport through the matrix in the fractured tuff and in the alluvium. Due to lack of information on fracture mineralogy and relatively rapid travel times, it is assumed that there is no retardation (i.e., $K_d = 0$) in fractures for all nine RNs tracked in PA. Sorption coefficients in the matrix were assigned probability distributions based on expert elicitations conducted for earlier TSPA efforts.

In the DOE TSPA-VA, the basis for the values used for alluvium sorption parameters (TRW Environmental Safety Systems, Inc., 1998, Chapter 8, Section 8.4.2, p. 8–54) for the suite of nine RNs is the compilation of Thibault, et al. (1990). For application of these parameters in the vicinity of YM, distributions were derived by assuming the presence of oxidizing conditions and the presence of at least 5 percent calcite. The sorption coefficients are also scaled by effective porosity ($n_{effAL}$) in the alluvium to define an effective sorption coefficient as:

$$(\hat{K}_d) = K_d \frac{n_{effAL}}{n_{AL}}$$

The DOE performed sensitivity analyses using the TSPA-VA code to investigate the effects of uncertainty in sorption parameters on performance. In the SZ, sensitivity analyses focus on the length of the alluvium path (0–6 kilometers, TRW Environmental Safety Systems, Inc., 1998, Section 8.4.2, p. 8–51). This length is considered to be a parameter of interest because of "… a larger sorption capacity for neptunium and selenium …" (TRW Environmental Safety Systems, Inc., 1998, Section 8.4.2, p. 8–51). Sensitivity analyses were not conducted to investigate the effects of uncertainty in alluvium sorption coefficients on performance. The effects of uncertainty in sorption of neptunium in the SZ volcanic tuffs were investigated using a sensitivity analysis, but the $K_d$ for neptunium sorption in the alluvium was held constant at 10 mL/g (TRW Environmental Safety Systems, Inc., 1998, Section 8.5.2.3.2, p. 8-84 to 8-85).

### 5.3.1.9.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Radionuclide Transport in the Saturated Zone

The SZ at YM is composed of porous rock and fractured rock that constitutes the RN pathway from the water table under the repository to the critical group. Most of the YM geochemical work in the past 20 years has been directed toward determining the retardation of RNs in porous rock. Significant progress has been made to address this issue (one of the subissues of the Radionuclide Transport Issue Resolution Status Report, Revision 1) that is important to waste isolation and repository performance.

The NRC staff (U.S. Nuclear Regulatory Commission, 1999c) finds that the approach adopted by the DOE (Triay, et al., 1992) to validate $K_d$ values from batch sorption tests is logical and defensible. By performing batch sorption tests using site-specific materials, followed by confirmatory tests to establish the validity of the assumptions needed for the constant $K_d$ approach, and then selecting the minimum $K_d$ from all the tests, an acceptable value can be obtained.

Overall, the NRC staff considers that the RT subissue dealing with RT through porous rock in the SZ has been resolved for certain RNs but not for others. Some of the RNs for which the subissue has not been resolved on the staff level may be important to performance. Three RNs are chosen as examples to highlight successes and areas needing further work. They are neptunium, plutonium, and uranium. The minimum $K_d$ approach has worked well for neptunium. The staff recognizes that multiple tests have been performed to establish reasonable $K_d$ values for this RN. Consequently, this subissue is resolved for neptunium. On the other hand, although both batch sorption tests and flow-through column tests have been performed to determine a minimum $K_d$ for plutonium, significant inconsistencies have been observed. The NRC staff recognizes plutonium as problematic and encourages further work to establish defensible $K_d$ values. For uranium, geochemical modeling suggests that a uranyl silicate phase, soddyite, could precipitate from solution, given the initial groundwater composition. Eliminating the possibility that processes other than sorption may be contributing to the removal of an RN from solution is necessary for establishing a valid $K_d$. On the other hand, the thermodynamic modeling could be in error, based on parameter uncertainties. To date, it does not appear that flow-through column tests were performed with uranium. Consequently, this subissue has not been resolved at the staff level.

With regard to RT through fractured rock in the SZ, current PA calculations (U.S. Nuclear Regulatory Commission, 1999h; U.S. Department of Energy, 1998a), assume no retardation in fractures, and RNs are transported through the fractures at the same velocity as groundwater. Under these conditions, flow issues related to F/M interaction and fracture flow velocity are the critical aspects of RT. These flow issues are considered as part of the USFIC KTI, and the reader is referred to the USFIC IRSR (U.S. Nuclear Regulatory Commission, 1999h) for an analysis.

However, experiments have been performed using fractured rock (Triay, et al., 1997). Whereas the retardation factor in fractures is typically assumed to be 1 (i.e., no sorption) in PAs, due to the uncertainty with regard to RT in fractured rock, preliminary experiments suggest that some retardation occurs. For example, neptunium experiments have been performed and show reduced recovery and a delay in the breakthrough relative to tritium and technetium. Field-scale experiments (30–100 meters) being conducted in saturated tuffs at the C-well complex (Reimus and Turin, 1997; Reimus, et al., 1998) result in bimodal breakthrough curves for nonreactive tracers (polyfluorinated benzoic acids, bromide), reactive solutes (lithium), and microspheres.

Reimus, et al. (1998) suggest that fast pathways and diffusion from the fracture into the matrix may play a role in SZ transport (Reimus, et al., 1998). However, resolution of this subissue will depend on a combination of laboratory experiments by DOE and additional tracer tests like those at the C-well field site.

Unlike the estimation of transport in porous media, which is supported by 50 years of chemical engineering experience in chromatographic separation techniques, the estimation of transport through fractured rock is relatively untested. The C-well reactive tracer test is the only field test of which the NRC staff is aware that provides direct information on the transport of reactive, nonreactive, and colloidal material in the SZ at YM. The C-well breakthrough curves (concentration and travel time) could not be quantitatively predicted using the laboratory experiments, including batch sorption, crushed tuff column, diffusion, and fractured rock column tests, alone, or in concert with the hydraulic pump tests in the C-wells.

The NRC staff considers the cross hole reactive tracer tests, like those at the C-wells complex and the Busted Butte facility, to be crucial to demonstrate the capability to predict transport. The use of field tests to compare back to the laboratory experiments is a logical extension to the strategy proposed by Triay, et al. (1992) to validate the batch sorption data. Geostatistical analysis of multiple tracer tests could be used to demonstrate the capability to predict RT in fractured rock.

For RT through the alluvium, additional uncertainty results from the very limited information collected to date on the mineralogy, groundwater chemistry, and flow systems of the alluvium. Past efforts by the DOE have focused on characterizing the geologic media within 5 km of the repository. With the resultant increase in the length of the flowpath to the biosphere to 20 km, consistent proposed for 10 CFR Part 63 (U.S. Nuclear Regulatory Commission, 1999a), a significant portion of relatively uncharacterized geologic media has been added to the system.

Although the NRC staff currently assumes in its TPA code (Mohanty and McCartin, 1998) that the alluvium acts as a homogeneous porous medium, it is recognized that little or no information is available to support that assumption. Furthermore, it is recognized that the staff's current assumption may be nonconservative.

The NRC staff expects that the series of boreholes to be drilled in the alluvium as part of the Nye County Early Warning Drilling Project (EWDP) will provide significant information concerning its geologic and hydrologic characteristics. It is expected that the mineralogy will reflect that used in batch sorption experiments for determining $K_d$s for RNs in tuff. Through early 1999, the EWDP had drilled eight wells to the south of YM. Lithologic logs available through the Nye County website (Nye County, 1999) indicate that much of the alluvium consists of valley fill deposits of gravel, silt, and sand varying in thickness from 33 m (110 ft) in well NC–EWDP–3S to more than 490 m (1618 ft) in well NC–EWDP–2D.

The determination of the modes of flow in the alluvium will require field tests. If the alluvium is a composite of cut and fill structures resulting from the accretion of anastamosing channels, preferred pathways limiting water-rock interaction may result. Criteria associated with the subissue on RT in fractured rock would then apply. If, on the other hand, the alluvium is homogeneous, the application of experimentally determined $K_d$s to calculate retardation factors would be appropriate. Resolution of this subissue will await the geologic and hydrologic information to be collected in the Nye County EWDP.

#### 5.3.1.10 Volcanic Disruption of Waste Packages

The discussions that follow for the DOE approach to abstracting volcanic disruption of waste packages into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of volcanic disruption of waste packages.

##### 5.3.1.10.1 Description of the U.S. Department of Energy Approach—Volcanic Disruption of Waste Packages

The latest iteration of DOE's TSPA (U.S. Department of Energy, 1998a) modeled the impacts of volcanic disruption of WPs through: (i) the direct release of RNs; (ii) an enhanced source term due to additional failure of WPs; and (iii) indirect effects of volcanic activity on transport of RNs in the SZ.

DOE's TSPA-VA (U.S. Department of Energy, 1998a) for YM attempted to perform more detailed modeling than previous TSPAs regarding the interaction of magma with the WP and transport of SNF out of the repository. Details of the DOE approach are presented in the IA IRSR (U.S. Nuclear Regulatory Commission, 1999i). The most important processes used by the DOE to model volcanic disruption of the WP are:

- A volcanic conduit forms outside the repository 62.7 percent of the time that volcanic disruption of the repository is modeled

- Volcanic conduits have a log-normal distribution in size, with a mean diameter of 50 m and a maximum diameter of 120 m

- WPs located within the volcanic conduit would not fail unless the WP had experienced at least 160,000 years of corrosion

- For WPs that failed in the volcanic conduit, HLW was not removed from the breached WP in 50 percent of the models

The DOE concluded in the TSPA-VA that volcanic disruption of the proposed repository site would have no impact on repository performance during the first 10,000 years postclosure (U.S. Department of Energy, 1998a).

##### 5.3.1.10.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Volcanic Disruption of Waste Packages

The NRC has just recently received many of the draft AMRs, that will be used to support the Site Recommendation Considerations Report (SRCR). While these reports are draft and the staff has not had time to completely review them, it is important to note that the information presented in these reports and information that was presented at the DOE/NRC Technical Exchange on TSPA-SR, on June 6–7, 2000, suggest some major modifications in the DOE analysis. For example, DOE has modified both the ash grain size and the waste form grain size. While questions remain, it appears that these grain-size distributions are better technically justifiable than values used during VA. As a result, Slide Number 11 of the M. Sauer (June 7, 2000, Technical Exchange, TSPA-SR Models: Disruptive Events) presentation appears to indicate that the DOE is able to replicate the 1995 Cerro Negro eruption with the ASHPLUME Code. DOE appears to be making significant progress in this area and may be able to resolve the NRC concerns with this ISI prior to licensing. Results of the two technical exchanges conducted at the end of August 2000, to discuss these and other concerns with the DOE's modeling of IA and the Biosphere, will be discussed in subsequent revisions to this IRSR.

Staff have numerous concerns with the analyses presented in the TSPA-VA (e.g., U.S. Nuclear Regulatory Commission, 1999i) as related to the volcanic disruption of the WP ISI. Overall, consistency was lacking for models used in calculations of: (i) volcanic disruption of the WP; (ii) airborne transport of RNs; (iii) mechanical disruption of the WP; and (iv) dilution of disruptive process derived RNs in soil. Details of these concerns are presented in the IA IRSR (U.S. Nuclear Regulatory Commission, 1999i). Summary concerns with the four most important processes used by the DOE are:

- Probability values used in PA are for a volcano forming at the proposed repository site. Model abstractions should accurately reflect underlying process models, such that volcanic disruption of the proposed repository occurs at a location and frequency supported by acceptable process models.

- The technical bases have not been presented for the range of conduit diameters used and the statistical form of the distribution. This range also does not address how magma may interact with repository drifts and disrupt more WPs than indicated by conduit diameters in undisturbed geologic settings.

- Data and models supporting WP and waste form resiliency during volcanic disruption lack sufficient technical bases, in that physical, chemical, and thermal conditions appropriate for YM basaltic volcanoes have not been examined.

- Data and models supporting a lack of HLW entrainment have not considered physical, chemical, and thermal conditions appropriate for YM basaltic volcanoes.

With current conservatism, staff analyses continue to demonstrate that volcanic disruption of the WP makes a contribution to total-system PAs. As such, the DOE will need to present an acceptable analysis of volcanic disruption of the WP processes in their LA. Informal communications with DOE staff since the release of the TSPA-VA have addressed many of these technical concerns with the volcanism risk calculations. DOE staff appear to recognize the need to develop additional models and data to support future DOE TSPA for IA. No changes to DOE performance models, however, were evident in the draft Environmental Impact Statement for YM (U.S. Department of Energy, 1999c).

#### 5.3.1.11 Airborne Transport of Radionuclides

The discussions that follow for the DOE approach to abstracting airborne transport of RNs into TSPA and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of airborne transport of RNs.

### 5.3.1.11.1 Description of the U.S. Department of Energy Approach—Airborne Transport of Radionuclides

DOE modeling of the airborne transport of RNs uses a modified version of the ASHPLUME code (Jarzemba, et al., 1997). This is the same code that the NRC uses to assess the airborne transport of RNs due to a volcanic event; so, most of the modeling assumptions are identical to the NRC assumptions. It is noted that use of the NRC code does not relieve the DOE from its responsibilities of demonstrating the adequacy of this code to model the airborne transport of RNs. DOE's model takes into account the possibility that the wind will not be blowing toward the critical group during the volcanic event. For these realizations, the quantity of tephra reaching the critical group location from the volcanic event will be small. DOE's model does not consider the redistribution of the contaminated tephra.

The DOE approach uses an empirical model for tephra dispersion developed originally by Suzuki (1983) and implemented in PA by Jarzemba (1997). This model abstracts the thermo-fluid-dynamics of tephra dispersion in the atmosphere using the following

$$X(xy) = \int_{\rho_{min}}^{\rho_{max}} \int_{O}^{H} \frac{5P(z)f(\rho)Q}{8\pi C t^{5/2}} exp[-\frac{5(x-ut)^2+y^2)}{8Ct^{5/2}}]dzdp$$

where $X$ is the mass of tephra and HLW accumulated at geographic locations $x, y,$ relative to the position of the volcanic vent; $P$(z) is a probability density function for diffusion of tephra out of the eruption column, treated as a line source extending vertically from the vent to total column height; $H$, $f$(ρ) is a probability density function for grain size ρ; $Q$ is the total mass of material erupted, $u$ is wind speed in the $x$-direction; $t$ is diffusion time of tephra, and $C$ is eddy diffusivity.

Suzuki's (1983) model has been modified and applied to volcanic eruptions by Glaze and Self (1991) and Hill, et al. (1998). Jarzemba (1997) applied the model to the transport of HLW during volcanic eruptions. In the Suzuki model, the eruption column is treated as a line source reaching some maximum height governed by the energy and mass flow of the eruption. A linear decrease in the upward velocity of particles is assumed, resulting in segregation of tephra or tephra and waste particles in the ascending column by settling velocity, which is a function of grain size, shape, and density. Tephra and HLW particles are removed from the column based on their settling velocity, the decreasing upward velocity of the column as a function of height, and a probability density function that attempts to capture some of the natural variation in the parameters governing particle diffusion out of the column. Dispersion of the tephra and HLW diffused out of the column is modeled for a uniform wind field and is governed by the diffusion-advection equation with vertical settling. Thus, results derived using this model depend heavily on assumptions about the shapes of the distributions $P(z)$ and $f(\rho)$. These distribution functions are empirically derived from analogous volcanic eruptions

### 5.3.1.11.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Airborne Transport of Radionuclides

Although it is completely appropriate to use the simplified models developed by Suzuki (1983) in PA analyses, it is crucial to delineate a physical basis for the parameter distributions used in the model. This is particularly important because the ASHPLUME model is essentially empirical, yet the dispersal of HLW in volcanic eruptions has never been observed. The use of inappropriate values for important factors in the model, such as particle-size distribution of the waste and incorporation ratio, could lead to an underestimate in the impacts of IA on the repository system. Under these circumstances, NRC review of the DOE analyses will use comparisons with other tephra dispersion models and limited physical analog modeling to evaluate assumptions about parameter distributions used by DOE.

NRC analyses with thermo-fluid dynamic models of the eruption column indicate considerable care is required in estimating $P(z)$ and $f(\rho)$ for dose calculations. Currently, DOE has not developed a basis for estimations of $P(z)$ and $f(\rho)$. In addition, if the DOE plans to take credit for variation in wind speed and direction, then it must evaluate redistribution of deposited tephra. Redistribution could lead to tephra that was originally transported away from the critical group to later be redeposited at the receptor group location.

Another important parameter in estimating dose is the particle-size distribution of HLW incorporated in the eruption column. In the TSPA-VA (U.S. Department of Energy, 1998a), DOE used *in situ* HLW particle-size distributions from Jarzemba and LaPlante (1996). These particle-size distributions were used in a preliminary analysis for volcanic disruption and did not consider particle-size degradation induced by mechanical, thermal, or chemical processes during igneous events, as outlined in NRC (1999i). These effects are important because the TSPA-VA uses a kinetic energy transfer model to entrain HLW from a breached WP. In this model, 50 percent of the simulations in TSPA-VA had HLW particle sizes that were too large to entrain from a breached container. Of the remaining 50 percent that entrained HLW, 70 percent of the simulations had eruption velocities that were too low to eject HLW from the volcano (U.S. Department of Energy, 1998a). Staff concludes that the HLW particle sizes used in the TSPA-VA need to be adequately justified. Overestimation of HLW particle sizes could result in underestimation of the amount of HLW potentially dispersed during a volcanic eruption.

### 5.3.1.12 Dilution of Radionuclides in Groundwater Due to Well Pumping

The discussions that follow for the DOE approach to abstracting dilution of radionuclides in groundwater due to well pumping into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of dilution of radionuclides in groundwater due to well pumping.

### 5.3.1.12.1 Description of the U.S. Department of Energy Approach—Dilution of Radionuclides in Groundwater Due to Well Pumping

In the TSPA-VA (U.S. Department of Energy, 1998a), the DOE has taken no credit for dilution due to pumping wells. This position is explicitly stated in the following excerpts:

> “There is no dilution during withdrawal of water from the aquifer; that is, there is no mixing of contaminated water with uncontaminated water when water is pumped from the ground or when water is stored in a tank.”

(U.S. Department of Energy, 1998a, Volume 3, Chapter 5, Section 5.8.2, Sensitivity of Dilution at the Well and the Biosphere)

> “No credit is taken for the pumping dilution in the basecase analyses of the reference design.”

(U.S. Department of Energy, 1998a, Volume 3, Chapter 6, Section 6.4.17, Dilution from Pumping)

DOE chose to assume that borehole RN concentrations are equivalent to the *in situ* centerline plume concentrations, which were calculated under the assumption that the flow-field remains unaffected by pumping. DOE’s model abstraction assumed that the well receives only contaminated water from the SZ. In the DOE TSPA-VA, no credit was taken for large-scale mixing induced by interbasin groundwater flow. Through an expert elicitation process on the SZ, large-scale mixing induced by interbasin groundwater flow was generally deemed insignificant, except in cases where regional flow is strongly affected by transient behavior. As a result, dilution factors reported in the TSPA-VA account only for micro-dispersive processes and are several orders of magnitude smaller than those reported in TSPA-95 (CRWMS M&O, 1995b).

#### 5.3.1.12.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Dilution of Radionuclides in Groundwater Due to Well Pumping

Because the DOE has not formally proposed either an approach for assessing dilution due to pumping or an abstraction methodology, an analysis of the DOE approach is not necessary at this time. It is unclear whether DOE will or will not explicitly account for borehole dilution in computing borehole RN concentrations in future versions of the TSPA. If DOE continues to take no credit for RN dilution in the well bore due to well pumping, this would be conservative and therefore acceptable to the staff. The acceptance criteria and review methods discussed in the following section will not be relevant.

If DOE decides to change strategy and take credit for radionuclide dilution due to well pumping, the staff review should determine that the maximum pumping rate used in the TSPA is realistic and defensible considering the critical group characterization and aquifer sustainable (safe) yield. In addition, the staff review should determine that the presumed uniform radionuclide concentration in the pumped water is realistic and defensible considering the water use and distribution practices at the receptor location.

### 5.3.1.13 Redistribution of Radionuclides in Soil

The discussions that follow for the DOE approach to abstracting redistribution of radionuclides in soil into total system performance assessment and NRC’s evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC’s evaluation of DOE’s approach to abstraction of redistribution of radionclides in soil.

#### 5.3.1.13.1 Description of the U.S. Department of Energy Approach—Redistribution of Radionuclides in Soil

The most recent DOE TSPA (U.S. Department of Energy, 1998a) calculates doses to the receptor individual based on an all-pathways dose calculation using the GENII-S code (Napier, et al., 1988; Leigh, et al., 1993) from both a volcanic ash blanket and contaminated soil from irrigation. The exposure dose from a contaminated surface soil layer is dependent on the residential and agricultural use of land on which the RNs have been deposited. The assumption is made that the contaminated land is farmed and used to grow food for local consumption. It is assumed that any contaminated material deposited on the ground surface is uniformly distributed through the upper 15 cm (6 in.) of the ground surface, because this is the plowing depth for most agronomic plants. The DOE also assumes that the root depth of all plants is 15 cm so that the roots have no access to uncontaminated soil for the uptake of nutrients, including radioactive isotopes of those (or related) elements.

DOE calculations of the effects of volcanic events are limited to the calculation of a peak dose in the year of occurrence of the volcanic event and do not account for the long-term reduction in RN inventory in the ash blanket in the area of the critical group. Processes that can change the RN concentrations over time such as leaching, surface erosion, radioactive decay, and surface water transport of contaminants from the Fortymile Wash watershed to the region of the critical group are not explicitly discussed in the TSPA-VA. Although mass-loading parameters are not identified for the tephra-fall deposits, TRW Environmental Safety Systems, Inc. (1998) uses an average mass load of $1.9 \times 10^{-5}$ g $m^{-3}$ for other dust inhalation scenarios.

In the TSPA-VA, the existing capability in the GENII-S code for modeling the process of RN accumulation in soil irrigated with contaminated groundwater has been used. This method does not account for long-term (greater than a year) buildup of RNs in soil. Soil concentrations are only tracked for a single year of irrigation; each following year starts with clean soil.

#### 5.3.1.13.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Redistribution of Radionuclides in Soil

DOE calculations of the effects of volcanic events are limited to the calculation of a peak dose in the year of occurrence of the volcanic event and do not account for the long-term reduction in RN inventory in the ash blanket in the area of the critical group. To appropriately calculate the expected annual dose, as demonstrated in Section 4.4.1.1, these processes should be characterized to determine the concentration of RNs in the soil following a volcanic event. In addition, the possible effects of erosion of the ash blanket in the upstream reaches of Fortymile Wash and deposition in the area of the critical group, which has the potential for either increasing or decreasing the expected annual dose, has not been considered in the TSPA-VA. The possible effects of leaching of the ash blanket and downward transport of these RNs to the groundwater system also have not been considered.

The mass loading factor used in dose modeling of the ash blanket in the TSPA-VA appears to significantly underestimate the amount of inhalable and respirable particulates suspended over undisturbed and mechanically disturbed tephra deposits. This is an important variable in determining the dose from a volcanic event, and the value used by the DOE in the TSPA-VA does not appear appropriate for the mass load above a fresh volcanic ash blanket.

The buildup of RNs in soil due to multiple years of irrigation with contaminated water is a process not considered in the TSPA-VA. If RNs remain in the root zone of plants over many years, this process could increase the dose to members of the critical group through many pathways, including ingestion of crops, ingestion of animal products, incidental ingestion of soil, and groundshine.

### 5.3.1.14 Lifestyle of the Critical Group

The discussions that follow for the DOE approach to abstracting lifestyle of the critical group into total system performance assessment and NRC's evaluation of the abstraction were current as of the VA documentation. The next revision of this report will provide an update of NRC's evaluation of DOE's approach to abstraction of lifestyle of the critical group.

#### 5.3.1.14.1 Description of the U.S. Department of Energy Approach—Lifestyle of the Critical Group

DOE's approach to calculating BDCFs in the TSPA-VA is similar to the NRC approach used in the TPA code and appears consistent with proposed NRC requirements for the reference biosphere and critical group in draft 10 CFR Part 63. DOE uses the same biosphere/pathway/dose models (GENII-S) (Leigh, et al., 1993) as NRC to calculate an annual dose to the average member of a 20-km farming group in Amargosa Valley. Most of DOE's input parameters are the same as used by NRC/CNWRA. The use of site-specific survey data for local demographics (Cannon Center for Survey Research, 1997) is an improvement over NRC/CNWRA modeling. Additional similarities and differences in approach to modeling the critical group abstraction are discussed in the following paragraphs. The assessment of dose in the TSPA-VA assumes that at the receptor location, groundwater is used for drinking, irrigation of crops, and water for livestock. Additional pathways for exposure of the critical group considered by the TSPA-VA include inhalation and inadvertent ingestion of contaminated soil and direct exposure by RNs in the environment.

#### 5.3.1.14.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Lifestyle of the Critical Group

The NRC has just recently received many of the draft AMRs, that will be used to support the Site Recommendation Considerations Report. While these reports are draft and the staff has not had time to completely review them, it is important to note that the information presented in these AMRs appear to directly address some of the staff concerns. The results of the review of these documents and the two technical exchanges to be conducted at the end of August 2000, to discuss these and other concerns with the DOE's modeling of igneous activity and the biosphere, will be discussed in subsequent revisions to this IRSR.

DOE values appear reasonable for soil, but could be low for ash, which is expected to include fine-grained particles that are likely to be more resuspendable than soil particles. The mass loading factor is an important, and uncertain parameter for use in calculating inhalation dose from the IA disruptive event. Therefore, a technically defensible basis for the chosen factors applicability to known or assumed volcanic ash characteristics is important as well. The potential lack of conservatism may be offset by DOEs use of a more conservative approach to calculating dose from the ash blanket (i.e., no accounting of dilution effects). Refer to the description of the ISI for dilution of RNs in soil for more information on dilution issues in this IRSR.

DOE's implementation of BDCFs for the critical group abstraction in TSPA modeling as described in the VA may introduce bias into the calculations. The VA indicates stochastic calculations in GENII-S (Leigh, et al., 1993) are run to generate RN-specific DCF distributions that are then sampled for each iteration of the TSPA. DOE correlates the sampling so that a large value selected for one RN leads to large value selections for all RNs for a given realization (TRW Environmental Safety Systems, Inc., 1998). In the past, the NRC/CNWRA considered sampling DCF distributions for the TPA in a manner consistent with the general approach taken by DOE, but abandoned the concept based on statistical and conceptual concerns.

One potential problem with DOE's stochastic approach was the possible introduction of bias from double sampling (first in the stochastic calculation of the DCF, then again in the sampling of BDCFs for each iteration of the TSPA). Another concern was that double sampling would de-couple the BDCFs from their original sampling vectors. Therefore, all re-sampled BDCFs for a given TSPA iteration would not be based on the same suite of input parameters. For example, the irrigation rate for the selected $^{241}$Am DCF is not the same as the irrigation rate for the selected $^{237}$Np DCF. Thus, conceptually, the biosphere and critical group characteristics would be incongruent among RNs in a given iteration of the code. DOE's statement that the BDCFs were correlated by the magnitude of the DCF is questionable because the various factors that contribute to the magnitude of BDCFs vary among RNs; thus the parameter selections that cause an increase in the $^{99}$Tc DCF will not necessarily increase the $^{129}$I DCF. The effect of this correlation is expected to increase the range of the dose distribution, but may not affect the mean dose. At a recent NRC/DOE technical exchange on PA, DOE indicated that this final concern may be offset by the importance of one or a few RNs to the total dose. This and other explanations for unique modeling approaches for the critical group abstraction may be adequate if fully justified and supported by calculation results. The existence of other strong evidence that the abstraction approach is not introducing a significant source of bias in PA calculations may also be adequate.

### 5.3.2 U.S. Nuclear Regulatory Commission Staff Evaluation - Total System Performance Assessment Integration and Abstraction

**AC TSPA adequately incorporates important design features, physical phenomena, and couplings and uses consistent and appropriate assumptions throughout the abstraction process.**

STAFF REVIEW:

The review for the integration component of model abstraction at the TSPA model-level focuses on the the couplings and information transfer between subsystems. In addition, consistent and appropriate assumptions are necessary throughout the performance assessment to satisfy the integration acceptance criteria. Review of the integration aspect between subsystems is a primary task of the TSPAI KTI. In addition, the TSPAI KTI will review the integration of subsystems with the TSPA model. Two key documents (the TSPA-SR technical report and the TSPA-SR model document) were not available to be included in the review completed for this evaluation. The documents that were reviewed by the TSPAI KTI included:

| | |
|---|---|
| Future Climate Analysis | (ANL-NBS-GS-000008 Rev. 00B) |
| Abstraction of Flow Fields for RIP | (ANL-NBS-HS-000023 Rev. 00) |

| | |
|---|---|
| Abstraction of Drip Seepage | (ANL-NBS-MD-000005 Rev. 00) |
| Seepage/Cement Interactions | (ANL-EBS-MD-000043 Rev. 00) |
| Inventory Abstraction | (ANL-WIS-MD-000006 Rev. 00) |
| Environment on the Surfaces of the Drip Shield and Waste Package Outer Barrier | (ANL-EBS-MD-000001 Rev. 00) |
| In-Drift Precipitates/Salts Analysis | (ANL-EBS-MD-000045 Rev. 00) |
| WAPDEG Analysis of Waste Package and Drip Shield Degradation | (ANL-EBS-PA-000001 Rev. 00) |
| Cladding Degradation - Summary and Abstraction | (ANL-WIS-MD-000007 Rev. 00) |
| Defense High-Level Waste Glass Degradation | (ANL-EBS-MD-000016 Rev. 00) |
| Summary of Dissolved Concentration Limits | (ANL-WIS-MD-000010 Rev. 00) |
| Particle Tracking Model and Abstraction of Transport Processes | (ANL-NBS-HS-000026 Rev. 00) |

It is not possible to fully review integration without the aforementioned documentation that is not yet available (TSPA-SR documents). However some comments and potential problems are discussed in the paragraphs that follow. It is anticipated that the next revision of this document will include a more complete review of system integration. In addition, when the NRC receives the GoldSim computational tool, a more complete review of system integration can be completed.

### 5.3.2.1 WAPDEG Analysis of Waste Package and Drip Shield Degradation

The *WAPDEG Analysis of Waste Package and Drip Shield Degradation* AMR describes the abstraction of drip shield and waste package degradation for use in the TSPA-SR. Two potential problems were identified related to abstraction and integration.

In the WAPDEG model, general corrosion rates are resampled halfway through the corrosion of the waste packages. Resampling during the corrosion process was initiated to account for temporal variation in the corrosion rates. It is doubtful that resampling of the general corrosion rates is an acceptable method to incorporate temporal variation (in the general corrosion rates). A second potential problem (identified via the review of the aforementioned documentation) was the application of Gaussian Variance Partioning (GVP) to different parts of the waste package failure time calculations, especially general corrosion. GVP is utilized to separate uncertainty and variability in various distributions of parameters utilized in the WAPDEG model. The basic concept is that a distribution of a parameter contains both uncertainty and variability. Variability is roughly defined as real differences in the parameter from place to place (waste package to waste package, patch to patch on a waste package, etc.) or with temporal evolution. From this point forward the discussion will be with respect to general corrosion rates (but will apply to any parameter for which GVP is applied). Variability results from mechanistic differences between general corrosion and material properties or the environment.  Uncertainty would be random, non-mechanistic perturbations caused by measurement errors or unquantifiable processes.

The DOE has stated that they are unable to quantify how much of the spread in the general corrosion rate distribution for the waste package results from uncertainty and how much results from variability.  Therefore, they randomly sample a splitting parameter from 0 to 1 (100% uncertainty to 100% variability).  In theory it is possible that the general corrosion rate data has variability.   However, quantification of the variability in the general corrosion data is difficult if not impossible due to the very low corrosion rates and the precipitation of silica during the experiments.  If a quantification of variability with environment can be made, then the temporal and spatial variation in the environment must be known and quantified.  Otherwise the application of GVP would be unacceptable.  The impact of using GVP (on the performance assessment) is likely complex.  Intuition suggests that peak doses (after the compliance period) will likely increase and also system sensitivity to other variables will increase as more uncertainty is assumed and less variability.  A simple way to test the impact of using GVP would be to implement 100% uncertainty (concurrently) for all parameter distributions that are being split.  This case could be compared to the case for 100% variability.   The use of GVP is a good example of an integration problem which stretches across numerous subsystem boundaries (waste package/drip shield, drift seepage, evolution of the near-field environment, thermohydrology).

#### 5.3.2.2 Summary of Dissolved Concentration Limits

The *Summary of Dissolved Concentration Limits* AMR describes the abstraction of solubility limits of radioactive elements based on process-level models.  The product of the abstraction was to develop solubility limits as functions, distributions, or constants for all transportable radioactive elements.  A potential integration/abstraction problem was identified during review of this AMR.

Elemental solubility limits were generated with EQ3/6 for a select number of radionuclides and expected in-package environmental conditions.  The results from the calculations were then abstracted as either functional relationships or probability distribution functions.  Some elements were abstracted to have constant solubility.  The AMR on in-package chemistry was not complete at the time of production of the summary of dissolved concentration limits AMR.  An estimate of the potential chemical environments inside the waste package was utilized in the solubility limits abstraction AMR.  The ranges selected for key chemical variables by the dissolved concentration limits AMR were more narrow than those generated by the in-package chemistry model.  An extrapolation was completed for the functional abstractions to generate solubility limits when the chemical environments are sampled outside of the range, however a similar evaluation was not completed for the probability distribution functions.  A similar problem to that discussed above was recognized with EQ3/6 calculations that would not converge due to numerical instability.  In effect the TSPA model would potentially sample a chemical environment for which select radionuclides had no corresponding solubility limit generated.

The abstraction of solubility limits is decoupled from the degradation of engineered barrier system components and the dissolution of waste form materials.  This decoupling potentially neglects the impact of dissolved uranium concentrations on pH.  A better argument is needed that the level of integration completed between solubility limits, degradation of repository materials (and waste), and the in-package chemical environment model is sufficient.

In addition, it is assumed that J-13 is the infiltrating water composition for the in-package chemistry model used to define the chemical environment for calculation of solubility limits. Therefore, evolution of the near-field environment is decoupled from the in-package chemistry calculation. This assumption may be valid for long waste package lifetimes (it depends on how long perturbations to chemistry may persist), but would not be applicable for many types of barrier underperformance calculations.

#### 5.3.2.3 Cladding Degradation - Summary and Abstraction

The *Cladding Degradation - Summary and Abstraction* AMR summarizes the degradation mechanisms for spent fuel cladding and the models for TSPA-SR. A number of concerns were identified during review of this AMR.

In the analysis of cladding degradation, triangular probability distribution functions were frequently used. For example, a triangular distribution defines the fraction of clad rods with creep failure as a function of temperature. For each temperature, T, there are three estimates of the fraction of failed rods: $f_l$ (lower limit), $f_b$ (best estimate), and $f_u$ (upper limit). At the temperature T, the fraction of failed clad rods is sampled from a triangular PDF with extremes $f_l$ and $f_u$, and $f_b$ as its peak. Note that the mean of this triangular PDF is not necessarily equal to the best estimate $f_b$. The position of the peak of the PDF should be adjusted so that its mean coincides with $f_b$, or it should be shown that the approach does not bias the results.

Some parameter distributions appear to have been selected without an appropriate consideration of uncertainty. For example, if three data values (*x1, x2, x3)* are available for parameter *x* then the distribution utilized to represent the parameter *x* will almost certainly have a true range which is larger than the minimum and maximum of *x1, x2,* and *x3*. An appropriate amount of conservatism should be used when limited data is available.

The model for localized corrosion is based on a mass balance that could be inappropriate and may underestimate the occurrence of localized corrosion. It is assumed that cladding is failed by localized corrosion when a clad ring of 1 cm length reacts with flouride to form $ZrF_4$. Thus the extent of localized corrosion attack is limited by the amount of flouride in solution. This assumption does not consider the possibility for flouride to be a catalytic species for localized corrosion; i.e., flouride could be an activator of the localized corrosion process without the formation of flouride salts. Technical bases is needed providing justification that reaction of flouride with cladding is the only feasible localized corrosion mechanism.

The model for localized corrosion states that the worst case scenario is to direct all of the incoming flouride to one fuel rod. Then when that fuel rod fails, the flouride is directed to another fuel rod. While this approach would be most conservative with respect to earliest possible failures (for the approach taken and parameter values selected), it may result in an underestimation of peak dose. If failure of cladding does not impact mean peak dose in the 10,000 year compliance period, then DOE should consider an abstraction which would more likely represent the physical process of flouride containing waters dripping through openings in a waste package and interacting with spent nuclear fuel cladding. It is unlikely that all of the flouride would be directed to one fuel rod.

A thermal threshold is utilized as the abstracted metric against which to evaluate the occurrence of stress corrosion cracking of cladding. A complete propagation of uncertainty is necessary when evaluating threshold phenomena. For example, seven thousand waste packages would be expected to have 7,000 different temperature vs. time histories. Propagation of uncertainty in waste age, package thermal loading, rock thermal conductivity, infiltration rate, material thermal conductivities, and many other parameters would be needed to evaluate maximum expected cladding temperatures. If all permutations were under the temperature threshold, then the abstraction of thermal responses could be done in bins. However, if some of the temperature profiles exceeded the threshold temperature, calculating the average temperatures for bins of packages would result in an underestimation of cladding failure due to SCC.

Seismic effects are recognized by the DOE to potentially have an effect on cladding lifetime. The DOE approach is to assume that seismic events that occur with a frequency smaller than 1.1E-6/yr will be sufficiently large enough to mechanically disrupt all of the cladding. To implement this failure mechanism, the DOE randomly samples to determine if a seismic event of sufficient magnitude has occurred in the 10,000 year compliance period. However, if the frequency is 1.1E-6/yr it would be expected that approximately 100 problems would need to be executed to observe one event. This method of abstraction into the TSPA is incorrect and may result in an underrepresentation of risk.

#### 5.3.2.4 Inventory Abstraction

The *Inventory Abstraction* AMR summarizes the screening of radionuclides to ensure that all radionuclides that would contribute significantly to dose were tracked in the TSPA. The importance of radionuclides was considered by grouping according to (i) initial inventory, (ii) dose conversion factors, (iii) radioactive decay, (iv) solubility, and (v) transport affinity.

The grouping of radionuclides based on solubility and transport properties appears to be too broad. The broad category divisions were coupled with the radionuclide inventory and can lead to inappropriate screening. For instance, $^{36}Cl$ was screened out when compared to the inventory of other slightly or non-sorbing radionclides. Based on TPA 4.0 base-case runs, $^{36}Cl$ is one of only three radionuclides that contribute to dose of the critical group over the 10,000 yr compliance period. The other two radionuclides that contribute to dose are $^{99}Tc$ and $^{129}I$. Both $^{99}Tc$ and $^{129}I$ have larger inventories than $^{36}Cl$ and are included in the TSPA-SR analysis. The last of the three radionuclides included in the DOE TSPA-SR analysis for the slightly or non-sorbing group was $^{14}C$, but $^{14}C$ has not been shown to contribute to dose in the TPA 4.0 base-case. Another example is $^{79}Se$, which has been screened from the analysis by the DOE. It is grouped in the soluble and moderately sorbing transport group. This group also contains elements such as neptunium and uranium which have significantly larger DCFs than selenium. However, selenium is more soluble than neptunium and uranium by several orders of magnitude and also is transported more quickly than neptunium and uranium. Thus, selenium could pose a greater risk to the critical group, especially at early times, but has been screened from the analysis.

There are several concerns with regard to the methodology used for screening radionuclides. The product of the inventory and the inhalation and ingestion DCFs for the radionuclide is not directly related to the risk that the radionuclide poses to the critical group, even when the solubility and transport properties in the geosphere of theradionuclide are accounted for. Processes that affect transport in the biosphere, such as uptake by plants and bioaccumulation, are not accounted for using this methodology. Also, the direct exposure pathway is not accounted for by this approach.

Thus, radionuclides for which ground shine constitutes a significant exposure pathway, such as $^{94}Nb$ and $^{126}Sn$, could be inappropriately screened using this methodology.

The inhalation dose conversion factor for $^{151}Sm$ is over two orders of magnitude larger than for $^{63}Ni$. The ingestion dose conversion factor for $^{151}Sm$ is only slightly less (less than a factor of 1.5 smaller) than for $^{63}Ni$. Because the inventories of $^{63}Ni$ and $^{151}Sm$ tend to be similar over the repository times through 1,000 years, there appears to be insufficient basis to screen out $^{151}Sm$ and yet consider $^{63}Ni$ for the human intrusion scenario.

The *Inventory Abstraction* AMR does not indicate how radionuclides that decay to radionuclides that are important to performance, but are not considered important to performance themselves, will be accounted for in the analysis.

#### 5.3.2.5 Environment on the Surfaces of the Drip Shield and Waste Package Outer Barrier

The purpose of the *Environment on the Surfaces of the Drip Shield and Waste Package Outer Barrier* AMR is to specify the environments on the surfaces of the drip shield and waste package that are consistent with the relevant environmental conditions. The AMR's on *In-Drift Precipitates/Salts Analysis* and *Seepage/Cement Interactions* are also pertinent to the discussion. In the discussion that follows, a description of the level of integration that DOE has completed to estimate the environments on the surfaces of the drip shield and waste package is presented. Then an example is discussed of a potentially complex interaction that requires a high-level of system integration (or conceptualization) to evaluate. A number of different processes need to be evaluated in order to estimate the chemical environment on the surfaces of the drip shields and waste packages including: thermohydrology, seepage, salt precipitation and dissolution, and THC coupled processes.

Even though uncertainty in thermohydrology will result in many different permuations of temperature/relative humidity responses, only one pair of temperature/relative humidity response was used as input for the *In-Drift Precipitates/Salts Analysis*. The method utilized to abstract relative humidity information to the other AMR's does acceptably remove the time variable from the relative humidity response. However, it is unclear that the approach taken effectively propagates the uncertainties in modeling of thermohydrology. In simplification, it is expected that both the temperature and relative humidity will define the potential hydration of deposited mineral phases and salts. A Low Relative Humidty (LRH) model is used when RH is less than 85% (and greater than 50%) and a 'High Relative Humidty (HRH) is utilized when RH is greater than 85%. It is assumed that all of the brine generated during a time interval flows out of the calculational element at the end of the time interval for the LRH model. No technical basis is provided for this potentially important assumption.

J-13 water was assumed as the composition of the infiltrating moisture. It was recognized that THC processes, degradation of rock bolts and tunnel support materials, and dissolution of grouts could modify the chemistry of water entering the drift. However the potential magnitude of the impact of these processes on the environment calculations was not assessed. Revision of the AMR will consider more samples of YM water. A need for more data on pore water chemistry was recognized.

The estimation of the environment on a waste package under an intact drip-shield did not consider the deposition of dust or the deposition of salts from the ventilation air.

The discussion that follows highlights a number of items. First, the evaluation of a feature, event, or process in isolation may lead to an inappropriate screening of the FEP from the performance assessment. Second, a very high-level of integration may be necessary to adequately assess repository performance. Finally, it is very difficult in the repository system to consistently select conservative parameter ranges or alternative conceptual models without propagating the effects through the performance assessment model.

It is expected that salts will form on the surface of the drip shield due to evaporation, boiling, and eventual dry-out of moisture in the near-field environment. Even with the EDA-II design, the dry-out region around emplacement drifts may extend 5 meters or more and persist for over 1000 years. If salts are expected to be deposited in the engineered barrier system environment, it is reasonable to expect that salts will be deposited in the near-drift environment. These deposited salts will be dissolved by infiltrating water upon decay of the thermal pulse. It is likely that the composition of water that returns to the engineered barrier system following the thermal pulse may be significantly different from J-13 or even pore water.

Experimentation by Rosenberg et al. demonstrated the importance of propagating uncertainty in water chemistry to evaluation of the environments on the surfaces of the drip-shield or waste package (Rosenberg et al., 1999). J-13 waters were demonstrated to evolve to a much different solution composition upon extensive evaporation compared to pore waters. The chemical divide process was believed to be the driving phenomena in the evolution of different brines. Without proper evaluation of variability and uncertainty in water chemistry, incorrect conclusions may be derived about the evolution of brines in the Yucca Mountain system. The same experiments by Rosenberg et al. demonstrated that upon rewetting large amounts of $Ca^{++}$ and $Cl^-$ were found in solution (10249 and 30359 mg/kg, respectively). A recognized arbitrary dilution of 100 ml was applied to the hydrated salts in order to perform chemical measurements. Without dilution the concentrations of calcium and chloride would be expected to be much larger. Because they are the dominant components in the rewetting fluid composition at the surface of the drip shields or waste packages, it is reasonable to expect that some portion of the deposited salts may be $CaCl_2$ or $Ca(NO_3)_2$. $CaCl_2$ and $Ca(NO_3)_2$ have deliquescence points of 164.27 and 151°C, respectively. These compare to the DOE selection of $NaNO_3$ at 120.59°C, which they have stated as being conservative. It is unclear that the selection of $NaNO_3$ is conservative considering the uncertainty and variability in evolution of the environments on the waste package surfaces.

The environment on the surfaces of the drip shield and waste package outer barrier were calculated assuming J-13 was the input chemical composition. Not only will THC processes potentially perturb the starting chemistry, but corrosion of rock bolts, other drift support materials, and grout around rock bolts will likely be sources of chemical perturbation from J-13. In addition, the lifetime of grout, rock bolts, and other materials would need to be evaluated under thermally perturbed conditions (THC water chemistry modification) and not via interaction with dilute fluid compositions, unless justified. For example, the source of calcium from the dissolution of grout can be estimated and would be expected to be much larger than the source of calcium in infiltrating J-13 water (when rock bolts are present which is roughly 30% of the repository). In addition, the chemistry would be potentially quite variable temporally and spatially due to the aforementioned features and processes. Thus the chemistry of fluids dripping onto hot drip-shield surfaces are likely quite different from J-13. The environment models and drip shield corrosion testing should consider local and temporal chemistry variation.

Once this modified water encounters the drip-shield surface, it will likely encounter salts and other deposited minerals formed during the dry-out period. If the scale formed on the surface had porosity, vapor pressure lowering would be expected in the pores of the scale. Vapor pressure lowering would effectively reduce the humidity at which fluids would adsorb on deposited salts. The surface temperature of the drip shield or waste package (when water is expected to be present and corrosion processes can initiate) would be higher compared to the case of no vapor pressure lowering. In addition, relatively humidity is modeled to increase smoothly from a reduced state back to a near ambient state. At the point when water first begins to absorb onto the most deliquescent salts, it is likely that relative humidity will not be increasing smoothly but have considerable temporal fluctuation. The temporal fluctuation may result from intermittent dripping nearby or convection cell type processes in the drifts. Regardless of the source of the fluctuations, the salts will likely hydrate and dry completely multiple times before becoming permanently hydrated. Each time the salts begin to hydrate they will pass through a state of extremely high ionic strength where none of the geochemical tools appear to be applicable. The size of the time-stepping utilized to evaluate this dynamic process may be important.

While minimization of seepage into the drifts may be advantageous with respect to transport of radionuclides, it may be detrimental to the evolution of chemical environments in the near-field. The limited and intermittent behavior of seepage would allow deposited salts and brines to persist for much longer periods of time compared to high advective flow rates.

While it is anticipated that the chemical environment under an intact drip-shield will be significantly more dilute than the environment on the outer surface of a drip-shield, a satisfactory evaluation of the environment on the surface of a waste package will need to include the process of dust deposition resulting from ventilation.

The analysis that is documented by the DOE is a vast improvement over TSPA-VA. However, the above discussion should highlight the limited nature of the level of integration that was completed by the DOE.

#### 5.3.2.6 Abstraction of Flow Fields for RIP

The AMR for *Abstraction of Flow Fields for RIP* documents the post-processing of UZ site-scale flow field that were simulated using TOUGH2. The scope of the documented work was limited to the post-processing of nine base-case flow-fields for each of two perched water models (18 total flow-fields). The flow-fields are used by FEHM for particle tracking simulations in TSPA-SR. The nine base-case flow-fields are comprised of three infiltration rates (low, mean, and high) for three different climate periods (present day, glacial transition, and monsoon).

The AMR contained no discussion of potential effects on the UZ flow-fields from igneous or seismic activity (i.e. matrix or fracture alteration), thermal loading (i.e. geochemical transformation), or any other activities besides varying infiltration rates and perched water conditions. While an argument can be made that the perturbation of the flow-fields resulting from thermohydrological effects will be minimal at the expected time of radionuclide release, the flow fields would not be applicable for any type of underperformance calculation that resulted in early release from the waste packages. In addition, the level of integration for the other potential effects appears to be inadequate unless a technical bases can be provided that their affect on repository performance will be minimal.

STATUS:

Open. Even though a limited number of abstraction AMR's were reviewed in time for preparation of this document, a fair number of integration and higher-level abstraction concerns were identified. It is anticipated that NRC staff will provide a more complete review of integration upon receipt of the TSPA-SR technical and TSPA-SR model documents. In addition, receipt of GoldSim will allow NRC performance assessment staff to do a thorough evaluation of model integration and abstraction. NRC PA staff acknowledges that an improvement has been made over the TSPA-VA.

## 5.4 DEMONSTRATION OF THE OVERALL PERFORMANCE OBJECTIVE

The review for the demonstration of the overall performance objective focuses on the methodology that the DOE will use to demonstrate that the overall performance objective has been met. Resolution of the subissue does not rely upon comparison of the numerical results of the DOE TSPA to the applicable regulatory limit. This comparison can only be made after closure of all KTI subissues and must be based on the final calculations presented in the DOE LA. Closure of the subissue will simply indicate that NRC staff have no further questions about the methodology that DOE will utilize to demonstrate that the overall performance objective has been met.

The issue resolution review for the demonstration of the overall performance objective covers the following areas: (i) calculation of expected annual dose; (ii) demonstration that expected annual dose does not exceed regulatory limits; (iii) confidence in TSPA results; (iv) human intrusion; (v) comparison of alternative design features. The staff review for issue resolution is based on the following set of questions identified under each area of review.

*Calculation of Expected Annual Dose*

- Have adequate TSPA calculations been performed for all scenario classes that were not screened from the TSPA?
- Has the expected annual dose as a function of time, including the undisturbed scenario class and all disruptive scenario classes, been appropriately calculated?

*Demonstration that Expected Annual Dose does not Exceed Regulatory Limits*

- Are overall repository performance and the performance of individual components or subsystems consistent and reasonable?

*TSPA Model Confidence*

- Have sufficient numbers of realizations been run for each scenario class?
- Has a sufficient number of realizations of the TSPA code been conducted to ensure that the results of the human intrusion calculation are statistically stable?

- Are assumptions made within the TSPA code consistent among different modules of the code or properly justified if different?
- Has the TSPA code been properly verified to provide confidence that the models are implemented in the code as intended and data transfer among modules is conducted properly?
- Does the estimate of uncertainty in the DOE TSPA results appropriately reflect the uncertainty in modeling assumptions and parameter values in the TSPA?
- Does the sampling scheme being used ensure that all sampled parameters are sampled across their range of uncertainty?
- Does the sampling scheme being used in the human intrusion calculation ensure that all sampled parameters are sampled across their range of uncertainty?
- Has the TSPA model been validated?
- Are the TSPA results insensitive to variation in time-stepping?
- Are the TSPA results insensitive to variation in TSPA-model discretization (i.e. the number of infiltration bins, the number of thermohydrology bins, the number of points radionuclides are input to the saturated zone, etc.)?

*Human Intrusion*

- Has the TSPA for human intrusion been performed separately from the overall TSPA?
- Is the TSPA for human intrusion performed in the same manner as the overall TSPA and does the human intrusion TSPA use the same critical group?
- Is the DOE modeling of human intrusion consistent with the stylized scenario specified in 10 CFR Part 63?
- Is the estimated repository performance reasonable and consistent with the characteristics with the analysis of overall repository performance and with the characteristics of the postulated intrusion event?
- Are assumptions made in the TSPA for evaluating human intrusion consistent among different modules of the code or properly justified if different?
- Is the estimate of uncertainty in the performance assessment results consistent with the uncertainties considered in the characteristics of the postulated intrusion event and with model and parameter uncertainty?

*Comparison of Alternative Design Features*

- Has DOE provided an adequate comparative evaluation of alternatives to the major design features that are important to repository performance including differences in repository performance and other considerations associated with the design?

This description and the evaluation by NRC/CNWRA of DOE approach are based on documents available to staff as of May 1, 2000 and information gained during the DOE/NRC Technical Exchange on TSPA on June 6–7, 2000. The primary documents reviewed include:

- Total System Performance Assessment—Site Recommendation Methods and Assumptions Report (CRWMS M&O, 1999a)
- Repository Safety Strategy Planning Report, Revision 03 (CRWMS M&O, 2000a)

### 5.4.1 Description of t he U.S. Department of Energy Approach—Demonstration of the Overall Performance Objective

DOE has indicated that TSPA calculations will be performed for the nominal scenario class (the scenario class in which no disruptive FEPs occur) and all disruptive scenario classes that cannot be screened on the basis of probability or consequence. The total number of scenario classes that will be considered in the TSPA will be determined by the combinations of the occurrence and nonoccurrence of disruptive events. Previous TSPAs (U.S. Department of Energy, 1998a) have focused on three disruptive scenario classes - igneous activity, seismic activity, and criticality. TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a) indicates that IA is expected to be treated as a disruptive event in TSPA-SR and that screening decisions for other disruptive events have not been completed. Further discussions at the DOE/NRC Technical Exchange on TSPA on June 6–7, 2000, indicated that IA would be the only disruptive event incorporated in the TSPA. Combinations of multiple disruptive events will be considered and included in a TSPA calculation if they cannot be screened on the basis of probability or consequence.

In the TSPA-SR Methods and Assumptions document, DOE has indicated that a conditional mean dose curve will be calculated for the nominal scenario class and all disruptive scenario classes with a probability above the NRC cutoff (i.e., the mean dose given that the scenario class occurs). These conditional dose histories for each scenario class will be weighted by their scenario probability of occurrence. Finally, all these probability-weighted dose histories will be summed to result in the expected annual dose.

DOE has indicated that a sufficient number of realizations will be conducted for the TSPA-SR analysis to provide a stable estimate of the expected annual dose. Analyses in TSPA-VA (U.S. Department of Energy, 1998a) were performed to show that 100 realizations were sufficient to yield stable results. These analyses consisted of comparing the nominal scenario class performance measure generated with 100 realizations to that generated using a significantly larger number of realizations (three to ten times as many).

In TSPA-VA (U.S. Department of Energy, 1998a), intermediate outputs were presented for many subsystems to provide insight into the factors that were driving performance. These intermediate outputs included seepage flux as a function of time, WP failure time distribution, cladding failure as a function of time, radionuclide release rates as a function of time, groundwater travel times, dilution factors, and BDCFs. Based on presentations at the DOE/NRC Technical Exchange on TSPA on June 6–7, 2000, it appears that the use of the GoldSim® software (Golder Associates, Inc., 2000) will allow the presentation of many intermediate outputs, which should portray a clear picture of what is driving the performance of the system.

As indicated in Section 2.4 of TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a), all individual codes used in TSPA-SR will be placed under the CRWMS M&O configuration management program. This program includes software configuration identification, configuration control, and configuration status accounting. The configuration management program ensures that all individual computer codes used in the PA have been verified for use in the evaluation of the YM system. Verification will be in accordance with the AP-SI-1Q procedure (CRWMS M&O, 1999c). The use of the GoldSim® code (Golder Associates, Inc., 2000) will allow sufficient transparency of data transfer to demonstrate that transfer of data between modules of the code is being performed correctly. Validation will consist of comparison of the code results to field, laboratory, and natural analog data, or other computer codes that perform similar calculations to the code being validated.  At the DOE/NRC Technical Exchange on TSPA held on June 6–7, 2000, the presentation by McNeish described how the TSPA-SR models will be tested to ensure that the model adequately and reasonably represents the processes intended.  The TSPA-SR models will use controlled data inputs and checks will be performed to ensure that the information is being used as intended in TSPA-SR.  Intermediate results will be checked to ensure that subsystem linkages are being performed properly and the expected value case results will be checked to ensure that the overall system model is working correctly.

As indicated in Section 4.1.1 of TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a) and Section 2.1.3 of Revision 3 of the Repository Safety Strategy Planning Report (CRWMS M&O, 2000a), the uncertainty in the PA will be caused by several types of uncertainty.  Parameter uncertainty is uncertainty in the actual value of relevant parameters due to limited characterization and spatial and temporal variability.  Conceptual model uncertainty is uncertainty associated with the selection of the process model used to represent the available data.  Scenario uncertainty is uncertainty in the future evolution of the geologic environment surrounding the disposal facility such as whether and when certain events will occur.  All these types of uncertainty will be represented in the DOE TSPA.  Parameter uncertainty will be represented by sampling from ranges of parameter values using LHS.  Conceptual model uncertainty will be represented through the use of ACMs.  ACMs will be incorporated into the TSPA through either sensitivity studies, by weighing the results of the ACMs based on the probability of the model being correct, or by demonstrating that one model is more conservative than the other and using the more conservative model in the analysis.  Within the PMRs, many ACMs are identified, but very few are developed to the point of determining the effect of the ACM on intermediate outputs.  Scenario uncertainty will be incorporated into the TSPA by analyzing the consequences of each scenario independently.  For every scenario, each realization of the TSPA code will generate an equiprobable input data set that consist of parameter values randomly sampled from their prescribed ranges and distributions.  The result of each realization will be a conditional expected annual dose curve as a function of time.  The consequences of each scenario will be weighted by their probability of occurrence and the resulting average dose history from all the scenarios will be summed.  The mean of the calculated dose rates at each time step will be calculated to determine the expected annual dose.  Uncertainty in the results will be represented in two modes.  First, the standard deviation of the dose at each time step will be computed.  Second, the complimentary cumulative distribution function (CCDF) of the peak dose independent of time will be developed, which will indicate the probability of exceeding a given dose rate.

As indicated in Section 4.1.2 of TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a), the DOE will utilize LHS to ensure that the full range of uncertainty for each variable is sampled.  LHS consists of dividing the range of uncertain parameters into several intervals of equal probability and selecting a value at random from each interval without replacement (Helton, 1993) and is typically employed in conjunction with the restricted pairing technique (Iman and Conover, 1982) to ensure that the sampling algorithm imposes the desired correlation structure while eliminating spurious correlation due to the finite sample size.

The DOE approach for conducting a TSPA that assesses the effects of limited human intrusion on the repository system and demonstrates that the repository system is not substantially degraded as a result has been described recently in the TSPA-SR Methods and Assumptions document (CRWMS M&O, 1999a), Proposed Rule 10 CFR Part 963 (U.S. Department of Energy, 1999d), the Repository Safety Strategy Report (CRWMS M&O, 2000a), and in a presentation at the DOE/NRC Technical Exchange on June 6–7, 2000 (Freeze, 2000).  With a few exceptions, the

DOE approach is consistent with the requirements set forth in Proposed Rule 10 CFR 63 (U.S. Nuclear Regulatory Commission, 1999a).

The DOE has proposed to model two scenarios for limited human intrusion analysis that differ by their water contact mechanisms. The first scenario assumes increased water flow through the WP, damage to the invert and UZ barriers, and advective release of radionuclides. The second scenario assumes enhanced corrosion due to WP damage, minor damage to other barriers, and diffusive release of radionuclides. The first scenario closely resembles NRC's intent in proposed 10 CFR Part 63. The first scenario assumes that the event occurs 100 years following permanent closure and that a single borehole penetrates a WP and continues to the SZ. Advective release of radionuclides occurs as water from the surface percolates down the borehole into the WP and continues to the SZ.

In Section 4.6 of TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a), DOE has indicated that the reference design of the repository is expected to evolve during the detailed design process. Because the reference design of the repository has not been finalized, only limited analyses have been conducted on alternatives to the reference design. Discussions of alternatives to the reference design are primarily focused on the evolution of the reference design. Limited analyses were performed in TSPA-VA (U.S. Department of Energy, 1998a) to evaluate alternatives to the VA reference design. These analyses included the use of backfill, the emplacement of a drip shield over the WP, and the use of a ceramic coating over the WP. The TSPA-SR Methods and Assumptions document (CRWMS M&O, 1999a) indicates that alternative designs will continue to be investigated for the evolution of the reference design. Alternatives that have been indicated to be under consideration include the following:

- Extension of ventilation time and time of repository closure
- Changes in waste package design (e.g., size or material of construction)
- Invert design
- Drip shield design
- Backfill material, including removal of backfill
- Additional repository capacity

### 5.4.2 U.S. Nuclear Regulatory Commission Staff Evaluation—Demonstration of the Overall Performance Objective

**AC Scenarios used in the calculation of the expected annual dose as a function of time are adequate.**

STAFF REVIEW:

The methodology outlined by the DOE in TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a) is reasonable. Because the DOE has indicated that TSPA calculations will be performed for all scenario classes that cannot be screened from the TSPA, including scenario classes that include combinations of disruptive events, no additional information on the methodology is required at this time.

The methodology outlined by the DOE in TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a) to combine the probability and consequence of disruptive events into an expected annual dose curve seems to be reasonable. Weighting the conditional scenario class dose by the probability of occurrence of the scenario class over the time period of the calculation is consistent with the methodology outlined in Section 4.4 of this IRSR. Therefore, no additional information on the methodology is required at this time.

STATUS:

Closed. NRC will evaluate the implementation of the methodology to calculate the expected annual dose for all scenario classes in TSPA-SR to ensure that these calculations are being conducted properly.

**AC An adequate demonstration is provided that the average annual dose to the average member of the critical group in any year during the compliance period does not exceed 25 mrem TEDE.**

STAFF REVIEW:

The analyses performed in TSPA-VA (U.S. Department of Energy, 1998a) for the nominal scenario class were appropriate to demonstrate that stable results had been attained. However, similar analyses were not conducted for the disruptive scenario classes and the results from the IA scenario class were based on a very limited number of realizations that resulted in a release of radioactive material. It is not clear from the description in TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a) whether analyses would be conducted for disruptive scenario classes to demonstrate that sufficient realizations had been conducted to achieve a stable mean. However, discussions at the DOE/NRC Technical Exchange on TSPA indicated that many more realizations would be conducted for extrusive volcanism. The presentation by Sauer on Disruptive Events indicated that 100 realizations would be conducted for each time step for the time of occurrence of the event and that the time steps would be 25 years (Sauer, 2000). Although the DOE still needs to demonstrate that this number of realizations is sufficient to achieve a stable mean and that the methodology has been implemented correctly, the indicated number of realizations and timestep size seem reasonable. Additionally, DOE has indicated that process level modeling, which depend on uncertain parameters, will be utilized to determine probability distribution functions for uncertain parameters used in the TSPA, such as the seepage rate and the BDCFs. DOE should be able to demonstrate that these models have been conducted with a sufficient number of realizations to attain a stable mean.

Based on the intermediate outputs available in TSPA-VA (U.S. Department of Energy, 1998a), Section 2.6 of TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a), and the description of the Goldsim® software (Golder Associates, Inc., 2000) made during the DOE/NRC Technical Exchange on TSPA on June 6–7, 2000, it appears that a sufficient amount of information will be available on intermediate outputs in the TSPA to allow NRC staff to understand how individual components or subsystems contribute to system performance. The determination of whether the performance of the system is reasonable based on the behavior of individual components or subsystems cannot be made until the final analyses are completed for the LA.

The treatment of scenario and parameter uncertainty described in TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a) appears to be appropriate. The use of ACMs to represent model uncertainty is reasonable, but it is not clear whether these ACMs are being implemented correctly (see the more detailed discussion in the next section). NRC staff will continue to evaluate the implementation of the ACMs to determine whether they are being treated correctly in the DOE TSPA.

DOE has not indicated how it will support that the overall results of the TSPA code are reasonable and provide an estimate of performance that is consistent with or more conservative than the actual performance of the system. This overall system model support would provide more confidence in the results of the PA and could be performed using several different methodologies. For example, DOE could compare its results to the results of another PA developed for YM (such as by EPRI) to demonstrate that both results are comparable. This method could be used even if the results of the two codes were significantly different as long as DOE could explain why the differences between the two codes existed and provide justification for the approach used in its code. A method that could be used to provide support for the overall code results would be to utilize the outputs of the major repository subsystems to confirm that the results reported by the code are reasonable with hand calculations and to demonstrate the appropriate integration has been completed of the subsystems. Parameters such as the average number of WPs failed during the compliance period, the water flow rate through the waste package, the degradation rate of the spent fuel, the solubility of radionuclides, the travel time through the system for various radionuclides, the well pumping rate, and the BDCFs could be used in hand calculations to estimate the performance of the system. The DOE's quality assurance procedures are fairly explicit on what is required for model validation.

STATUS:

Open. The DOE must indicate how it will demonstrate that a sufficient number of realizations has been conducted for all scenario classes and all process-level models to ensure that the mean from each of these calculations is stable. DOE needs to provide a clear description of how the uncertainty in results due to model uncertainty will be incorporated into the TSPA results. NRC staff will evaluate the treatment of model uncertainty in TSPA-SR to ensure that the DOE does not imply that there is less uncertainty in the results than is warranted due to model uncertainty and that sufficient analysis has been done on the effects of ACMs on system performance. DOE should indicate how it will support the conclusion that the overall system model provides a reasonable or conservative representation of actual repository performance. The DOE must provide information to support that the results are stable considering the time-stepping utilized and the level of discretization for the TSPA-model.

**AC The TSPA code provides a credible representation of repository performance.**

STAFF REVIEW:

The use of QA procedure AP-SI-1Q to verify the overall system model and the use of the GoldSim® (Golder Associates, Inc., 2000) software to confirm that transfer of data between modules is being conducted properly appears to be sufficient to verify that the overall system model is implementing the individual process models as intended.

The treatment of scenario and parameter uncertainty described in TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a) appears to be appropriate. The approach outlined in the Repository Safety Strategy Planning Report, Revision 3 (CRWMS M&O, 2000a) for determining the effect of ACMs on performance using sensitivity studies, weighting the results of the ACMs based on the probability of the model being correct, or by demonstrating that one model is more conservative and using that one in the analysis is acceptable to NRC staff. The use of ACMs in sensitivity studies to illustrate the effect of the ACM on performance is a transparent method for incorporating ACMs into the PA. However, this methodology does not allow for the *model* uncertainty to be incorporated into the quantitative estimate of *parameter* uncertainty in the results of the PA. Therefore, discussions about the uncertainty in the PA should acknowledge that this type of uncertainty is not included in the quantitative estimate of uncertainty. Weighting the results of the ACMs based on the probability of the model being correct directly incorporates model uncertainty in the TSPA results. The analysis should be transparent enough for reviewers to determine the effect of the different ACMs if this methodology is utilized to account for model uncertainty. Additionally, there needs to be an appropriate technical basis for assigning the weights to the ACMs. The demonstration that one model is more conservative than other ACMs and the use of that model in the analysis is an appropriate methodology to provide confidence that the dose to the critical group for the repository system will not be underestimated. It is not clear whether DOE plans to analyze ACMs to determine their effect on intermediate outputs or on overall results. Additionally, it is not clear whether DOE will analyze the effect of ACMs for more than one process at a time that may interact with each other and potentially have a greater effect on the results than either ACM individually. The aforementioned approach (completing essentially a one-off replacement of an conceptual model with an alternative model) leads to the difficulties in determining which ACMs 'significantly' impact risk and which ones do not. When many ACMs exist, the number of permutations for combinations of ACMs becomes very large.

The methodology outlined by the DOE in TSPA-SR Methods and Assumptions (CRWMS M&O, 1999a) for sampling of parameter uncertainty seems to be reasonable. The use of LHS will ensure that parameters are sampled across their ranges of uncertainty. The use of LHS is acceptable as long as a sufficient number of realizations is conducted to ensure that the intervals in which the range of uncertainty is divided are not excessively large.

STATUS:

Open. DOE needs to provide additional clarification on how the results from ACMs will be incorporated into the TSPA results. NRC staff will evaluate the treatment of ACMs in TSPA-SR to determine whether sufficient analysis has been done on the effects of ACMs on the performance of the system. The evaluation of whether assumptions and parameter values are consistent among different modules of the code will be evaluated during the Model Abstraction review.

**AC Evaluation of an intrusion event demonstrates that the average annual dose to the average member of the critical group in any year during the compliance period is acceptable. The TSPA code provides a credible representation of the intrusion event.**

STAFF REVIEW:

The approach presented in the TSPA-SR Methods and Assumptions document (CRWMS M&O, 1999a) and the Repository Safety Strategy report (CRWMS M&O, 2000a) was generally acceptable. However, some differences between the DOE approach and proposed 10 CFR Part 63 do exist. These differences appear to be the result of DOE's attempt to develop an approach that is consistent with the set of three proposed rules from EPA (40 CFR Part 197), NRC (10 CFR Part 63), and DOE (10 CFR Part 963). Although there are several areas in which these rules are currently inconsistent, the NRC expects that the approach used by DOE for analysis of the limited human intrusion scenario will conform to the final regulations.

At the DOE/NRC Technical Exchange on June 6-7, 2000 (Freeze, 2000), DOE expressed a desire to exclude unlikely natural processes from the limited human intrusion analysis. This objective would be inconsistent with the NRC's proposed 10 CFR Part 63. Proposed 10 CFR Part 63 requires that the same assessment used for the nominal case be used for the human intrusion case, except for the addition of human intrusion. The NRC expects that the approach used by DOE for analysis of the limited human intrusion scenario will conform to the final regulations

At the TSPA DOE/NRC Technical Exchange on June 6-7, 2000 (Freeze, 2000), DOE expressed a desire to have the limited human intrusion event occur at a time greater than 10,000 years. This scenario is inconsistent with proposed 10 CFR Part 63. The NRC expects that the approach selected by DOE for analysis of the limited human intrusion scenario will conform to the final regulations.

Any parameter and scenario description choices made by DOE in development of an approach for human intrusion analysis must be justified. A few examples of scenario specifications that must be justified include, but are not limited to: water infiltration rates in the borehole, assumption of no gain or loss of water from or to the UZ, borehole dimensions, treatment of early-time vaporization, in-package temperature and chemistry, and credit for sorption in the UZ fault pathway. NRC expects that the approach selected by DOE for analysis of the limited human intrusion scenario will conform to the final regulations.

STATUS:

Closed pending - provided DOE's limited human intrusion analysis is conducted in accordance with final regulations and all scenario-specific assumptions are justified. To meet the acceptance criteria, DOE's human intrusion analysis must: (i) be performed separately from and be identical to the overall TSPA, except for the occurrence of a human intrusion event; (ii) assume the human intrusion event occurs 100 years after permanent closure of the repository; (iii) assume the human intrusion event takes the form of a drilling event that results in a single, nearly vertical borehole that penetrates a single WP, extends to the SZ, and is not adequately sealed; (iv) use the same critical group applied to the nominal case; (v) utilize calculations based on appropriate conceptual models and produce results that are reasonable and consistent with the available conceptual models and data; and (vi) show that the repository system meets NRC's performance objectives.

**AC An adequate comparative evaluation of alternatives to the major design features that are important to repository performance is provided.**

STAFF REVIEW:

Because the reference design of the repository has not been finalized, DOE has put only limited effort into the evaluation of alternative designs and development of the rationale for the selection of the reference design. The analyses of alternative designs in TSPA-VA (U.S. Department of Energy, 1998a) were insufficient to meet this acceptance criteria because only a limited number of effects of the alternative designs were considered. Significant interactions between the alternative design and the TSPA models were neglected which could alter the performance of the alternative design. For example, the analysis of backfill in TSPA-VA considered only the change in temperature in the drifts, but neglected the effects of the backfill on seepage and the effects of the backfill on the corrosion of the waste package. All significant effects of the alternative designs should be analyzed to determine the performance of the system using the alternative designs.

Other than the extension of repository capacity, the items under consideration for evolution of the reference design appear to be items that could be analyzed to meet the requirements for the comparative evaluation of alternatives to the major design features. It is anticipated that additional analyses of the performance of alternative design features will be conducted and arguments for the selection of the reference design will be provided following selection of a final reference design for the repository.

STATUS:

Open. DOE must define a reference design for the repository and describe the performance of the system for the reference design and designs that include alternatives to the major design features.

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# APPENDIX A:

# MAPPING OF INTEGRATED SUBISSUES TO U.S. DEPARTMENT OF ENERGY PRINCIPAL FACTORS

The U.S. Department of Energy (DOE) considers principal factors of the postclosure safety case are those central to determining and demonstrating long-term safety of the repository system (CRWMS M&O, 2000). More specifically, it defines the principal factors as the factors of the multiple barrier system necessary and sufficient to determine postclosure safety (Van Luik, 2000).

The principal factors identified in the Revision 3 of the Repository Safety Strategy (RSS) (CRWMS M&O, 2000) are:
(1.) Seepage into drifts
(2.) Performance of the drip shield
(3.) Performance of the waste package barriers
(4.) Solubility limits of dissolved radionuclides
(5.) Retardation of radionuclide migration in the unsaturated zone
(6.) Retardation of radionuclide migration in the saturated zone
(7.) Dilution of radionuclide concentrations during migration.

DOE will address an extended list of principal factors (Van Luik, 2000) in the Revision 4 of the RSS. The list includes:

(1.) Waste package performance (identified as critical to performance)
(2.) Seepage into emplacement drifts
(3.) Drip shield performance
(4.) Dissolved radionuclide concentrations
(5.) Colloid-associated radionuclide concentrations
(6.) UZ radionuclide travel time
(7.) SZ radionuclide travel time
(8.) Igneous activity—probability
(9.) Igneous activity—repository effects
(10.) BDCFs.

Tables A1 and A2 document the mapping of the principal factors to the U.S. Nucler Regulatory Commission integrated subissues.

**Table A1. Mapping of U.S. Department of Energy's principal factors in Revision 3 of the Repository Safety Strategy report to the U.S. Nuclear Regulatory Commission's integrated subissues**

| DOE Principal Factors included in Revision 3 of the Repository Safety Strategy Report | NRC Integrated Subissues |
|---|---|
| 1. Seepage into drifts | Quantity and chemistry of water contacting waste packages and waste forms<br>Climate and infiltration<br>Flow paths in the unsaturated zone |
| 2. Performance of the drip shield | Engineered barrier degradation<br>Mechanical disruption of engineered barriers<br>Quantity and chemistry of water contacting waste packages and waste forms |
| 3. Performance of the waste package barriers | Engineered barrier degradation<br>Mechanical disruption of waste packages<br>Quantity and chemistry of water contacting waste packages and waste forms |
| 4. Solubility limits of dissolved radionuclides | Radionuclide release rates and solubility limits |
| 5. Retardation of radionuclide migration in the unsaturated zone | Radionuclide transport in the unsaturated zone |
| 6. Retardation of radionuclide migration in the saturated zone | Radionuclide transport in the saturated zone |
| 7. Dilution of radionuclide concentrations during migration | Dilution of radionuclides in groundwater |

**Table A2. Mapping of the U.S. Department of Energy's principal factors proposed in Revision 4 of the Repository Safety Strategy report to the U.S. Nuclear Regulatory Commission's integrated subissues**

| DOE Principal Factors for Revision 4 of the Repository Safety Strategy Report | NRC Integrated Subissues |
|---|---|
| 1. Waste package performance | Engineered barrier degradation<br>Mechanical disruption of engineered barrier<br>Quantity and chemistry of water contacting waste packages and waste forms |
| 2. Seepage into emplacement drifts | Quantity and chemistry of water contacting waste packages and waste forms<br>Climate and infiltration<br>Flow paths in the unsaturated zone |
| 3. Drip shield performance | Engineered barrier degradation<br>Mechanical disruption of engineered barrier<br>Quantity and chemistry of water contacting waste packages and waste forms |
| 4. Dissolved radionuclide concentrations | Quantity and chemistry of water contacting waste packages and waste forms<br>Radionuclide release rates and solubility limits |
| 5. Colloid-associated radionuclide concentrations | Quantity and chemistry of water contacting waste packages and waste forms<br>Radionuclide release rates and solubility limits |
| 6. UZ radionuclide travel time | Radionuclide transport in the unsaturated zone |
| 7. SZ radionuclide travel time | Radionuclide transport in the saturated zone |
| 8. Igneous activity – probability | Volcanic disruption of waste packages<br>Airborne transport of radionuclides<br>Redistribution of radionuclides in soil |
| 9. Igneous activity – repository effects | Engineered barrier degradation<br>Mechanical disruption of engineered barrier<br>Quantity and chemistry of water contacting waste packages and waste forms<br>Volcanic disruption of waste packages |
| 10. Biosphere dose conversion factors | Dilution of radionuclides in groundwater<br>Redistribution of radionuclides in soil<br>Lifestyle of critical group |

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# APPENDIX B:

# LIST OF SUBISSUES IN U.S. NUCLEAR REGULATORY COMMISSION KEY TECHNICAL ISSUES

***Unsaturated and Saturated Flow under Isothermal Conditions (USFIC)***

USFIC1 Climate change

USFIC2 Hydrologic effects of climate change

USFIC3 Present-day shallow groundwater infiltration

USFIC4 Deep percolation (present and future)

USFIC5 Saturated zone ambient flow conditions and dilution processes

USFIC6 Matrix diffusion

***Thermal Effects on Flow (TEF)***

TEF1 Sufficiency of thermal-hydrologic testing program to assess thermal reflux in the near field

TEF2 Sufficiency of thermal-hydrologic modeling to predict the nature and bounds of thermal effects on flow in the near field

TEF3 Adequacy of total system performance assessment with respect to thermal effects on flow

***Evolution of the Near-Field Environment (ENFE)***

ENFE1 Effects of coupled thermal-hydrologic-chemical processes on seepage and flow

ENFE2 Effects of coupled thermal-hydrologic-chemical processes on waste package chemical environment

ENFE3 Effects of coupled thermal-hydrologic-chemical processes on chemical environment for RN release

ENFE4 Effects of thermal-hydrologic-chemical processes on radionuclide transport through engineered and natural barriers

ENFE5 Effects of coupled thermal-hydrologic-chemical processes on potential nuclear criticality in the near field

***Container Life and Source Term (CLST)***

CLST1 Effects of corrosion on the lifetime of the containers

CLST2 Effects of phase instability of materials and initial defects on the mechanical failureand the lifetime of the containers

CLST3 Rate at which radionuclides in SNF are released from the EBS through the oxidation and dissolution of spent fuel

CLST4 Rate at which radionuclides in HLW glass are leached and released from the EBS

CLST5 Effect of in-package criticality on WP and EBS performance

CLST6 Effect of alternate EBS design features on container lifetime and RN release from the EBS

***Radionuclide Transport (RT)***

RT1 RT through porous rock

RT2 RT through fractured rock

RT3 RT through alluvium

RT4 Nuclear criticality in the far field

***Total System Performance Assessment and Integration (TSPAI)***

TSPAI1 System description and demonstration of multiple barriers

TSPAI2 Scenario analysis within the TSPA methodology

TSPAI3 Model abstraction within the TSPA methodology

TSPAI4 Demonstration of the overall performance objective

***Activities Related to Development of the U.S. Nuclear Regulatory Commission High-Level Waste Regulations (ARDR)***

Not applicable (No IRSR planned because rulemaking is the product)

***Igneous Activity (IA)***

IA1 Probability of future igneous activity

IA2 Consequences of future igneous activity

***Structural Deformation and Seismicity (SDS)***

SDS1 Faulting

SDS2 Seismicity

SDS3 Fracturing and structural framework of the geologic setting

SDS4 Tectonic Framework of the Geologic Setting

***Repository Design and Thermal-Mechanical Effects (RDTME)***

RDTME1 Implementation of an effective design control process within the overall quality assurance program

RDTME2 Design of the geologic repository operations area 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 in meeting postclosure performance objectives

# APPENDIX C:

# SUMMARY OF REVIEW RESULTS FOR THE CRITICALITY FEATURES, EVENTS, AND PROCESSES

This appendix presents a summary of review results for the primary criticality FEPs. Table C-1 provides a justification for the FEPs resolution for the primary criticality FEPs reported in Table 5. DOE's FEP Name, Description, and Screening argument information presented in this table was obtained from the preliminary FEP Database (U.S. Department of Energy, 1999). The rationale for the staff conclusions in Table 5 for the primary criticality FEPs are provided in the review comments of Table C-1. Although reference is often made to a Criticality PMR for the primary FEPs within the database, neither PMRs nor AMRs exist for nuclear criticality. Instead, further treatment of nuclear criticality is provided in the Disposal Criticality Analysis Methodology Topical Report (U.S. Department of Energy, 1998). A detailed evaluation of the overall methodology and the approach in modeling and validation contained within the Disposal Criticality Analysis Methodology Topical Report is outside the scope of this report and is provided by the Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report, Revision 0 (U.S. Nuclear Regulatory Commission, 2000).

The Disposal Criticality Analysis Methodology Topical Report does not directly address the criticality FEPs but rather groups the features, events, and processes into scenarios, configurations, and configuration classes. Scenarios are the highest order grouping and consist of (i) criticality internal to the waste package (IP), (ii) external criticality in the near-field (NF), and (iii) external criticality in the far-field (FF). The scenario configuration classes are subdividisions of the scenario groups and represent a set of similar configurations resulting from a certain series of events. The scenario groups are contained within the scenarios and are designated by a number after the scenario acronym. The configurations are determined by the amount and location of the materials affecting criticality and represent the lowest level of organization.

In general, most of the configuration classes of the Disposal Criticality Analysis Methodology Topical Report correspond with primary criticality FEPs within the database. However, of the 31 configuration classes, ten corresponded to secondary FEPs. In some cases, a single FEP accounted for multiple configuration classes. Perhaps each configuration class from the Criticality Topical Report should correspond to a unique FEP within the database. There are also cases in which FEPs consider related events are not specifically contained within the Disposal Criticality Analysis Methodology Topical Report. The remainder of this section addresses the relationship, determined by the reviewer, of the secondary criticality FEPs to the configuration classes in the Disposal Criticality Analysis Methodology Topical Report (U.S. Department of Energy, 1998). The specific comments and findings are presented here according to the scenario designations: Criticality Inside the Waste Package, Near-Field Criticality, and Far-Field Criticality. The DOE needs to provide a clear mapping of FEPs to configuration classes discussed in the Criticality Topical Report. The next few paragraphs summarize NRC staff's crosswalking of FEPs and configuration classes.

*Criticality Inside the Waste Package*

The primary FEP *(2.1.14.03.00)* involves the WP internal structures degrading faster than the waste form, a top breach, and significant amounts of the neutron absorber being flushed out the top of the WP. Because configuration class IP-3a from the Criticality Topical Report involves the structural collapse of the fuel supports but does not involve flushing of the neutron absorber, the primary FEP *(2.1.14.03.00)* and its secondaries do not contain configuration class IP-3a. This should be explicitly considered by adding another FEP to the database.

While the secondary FEP *(2.1.14.03.01)* relates to configuration class IP-3b, the secondary FEP *(2.1.14.03.02)* seems to account for both configuration classes IP-3b and IP-3c.

Configuration class IP-2a is addressed by primary FEP *(2.1.14.04.00)*.

Configuration class IP-1b is addressed by primary FEP *(2.1.14.05.00)*.

Configuration class IP-1a is addressed by primary FEP *(2.1.14.06.00)*.

The primary FEP *(2.1.14.07.00)* involves a bottom breach of the WP. Significant amounts of the neutron absorber are either flushed from the WP or remain distributed throughout the WP, while fissile material collects at the bottom of the WP. This FEP corresponds to configuration classes IP-4a, IP-5a, and IP-6a, which relate to the WP degrading at slower, similar, and faster rates, respectively, than the waste form.

The primary FEP *(2.1.14.08.00)* involves a bottom breach of the WP, which does not allow water to collect in the WP. Moderation is provided by water trapped in clay or oxides. The waste form degrades in place and the neutron absorbing material mobilizes away from the waste form. This primary FEP, and its secondaries, appear to correspond with configuration class IP-4a. Although configuration class IP-4a involves the hydration of waste form degradation products in their initial location, it does not appear to account for the mobilization or removal of the neutron absorbers (as in the secondary FEPs of *(2.1.14.08.00)*). Such a scenario would not be conservative. Therefore, the Criticality Topical Report should be verified to ensure that mobilization or removable of the neutron absorbers are considered for configuration class IP-4a.

*Near-Field Criticality*

The primary FEP *(2.1.14.09.00)* and its nine secondary FEPs address configuration classes NF-4a and NF-5a in addition to other related events. Secondary FEP *(2.1.14.09.05)* seems to relate to configuration class NF-4a and involves the corrosion of the container and cladding, which releases more or less disintegrated fuel pellets (distribution of particle sizes) into a flooded geometry. However, configuration class NF-4a also involves the flushing of the neutron absorbers, which would increase the likelihood of criticality and should be considered in the primary FEP *(2.1.14.09.00)* and its secondary FEPs. Configuration class NF-5a does not explicitly mention separation of the fissile materials from the neutron absorbers. For conservative criticality calculations, consideration of the separation of the fissile materials from the neutron absorbers should be verified.

Configuration class NF-1c relates to the primary FEP *(2.1.14.10.00)*. The primary FEP *(2.1.14.10.00)* accounts for near-field criticality from a fissile material-bearing solution flowing into a drift low-point when the neutron poison has already been separated from the FM-bearing solution. However, only one of the three scenario branches for configuration class NF-1c explicitly mentions separation of the waste form from the neutron absorbers. The secondary FEPs *(2.1.14.10.02)* and *(2.1.14.10.03)* both address scenarios for separation of the neutron absorbers. For the configuration class NF-2a, separation of absorbers and fissile material is inlcuded as an event but is not listed in the configuration classes of the NF-1 scenario group. Therefore, the Criticality Topical Report should be verified to ensure that mobilization or removal of the neutron absorbers are considered for scenario configuration class NF-1c.

Configuration classes NF-1a and NF-1b correspond to the primary FEP *(2.1.14.11.00)*. Configuration class NF-1a accounts for sorption of the fissile material solutes in the tuff or concrete, and configuration class NF-1b accounts for precipitation of the fissile material by tuff. The primary FEP *(2.1.14.11.00)* addresses near-field criticality from a fissile solution adsorbed or reduced in invert (concrete and crushed tuff). The single secondary FEP *(2.1.14.11.01)* addresses the differential solubility of fissile isotopes.

Configuration classes NF-2a and NF-3a correspond to the primary FEP *(2.1.14.12.00)*. Configuration class NF-2a accounts for a fissile material slurry that flows to conform with the invert surface and separates with the neutron absorbers, and configuration class NF-3a accounts for the filtration and concentration of the fissile material colloids on top of the invert. The primary FEP *(2.1.14.11.00)* addresses a near-field criticality resulting from a slurry or colloidal stream being filtered (i.e., neutron absorbers are removed) by WP corrosion products and collecting on top of invert surface.

Configuration class NF-3b and NF-3c corresponds to the primary FEP *(2.1.14.13.00)*.

*Far-Field Criticality*

Configuration classes FF-3c, FF-3d, and FF-3e correspond to the primary FEP *(2.2.14.02.00)*. The secondary FEPs *(2.2.14.02.01)* and *(2.2.14.02.02)* correspond to the configuration classes FF-3d and FF-3e, precipitation at reducing zones with organics in an alluvial aquifer and the Franklin Lake playa, respectively. However, there is no secondary FEP that specifically deals with configuration class FF-3c, fissile material precipitates at reducing zones with remains of organic material.

Configuration class FF-1b corresponds to the primary FEP *(2.2.14.03.00)* and the secondary FEP *(2.2.14.03.01)*.

Configuration class FF-3a corresponds to the secondary FEP *(2.2.14.04.01)* under the primary FEP *(2.2.14.04.00)*.

Configuration class FF-3b corresponds to the secondary FEP *(2.2.14.04.02)* under the primary FEP *(2.2.14.04.00)*.

Configuration class FF-1c corresponds to the primary FEP *(2.2.14.05.00)*. However in the preliminary draft of the *Correspondence between YMP Database Criticality FEPs and the Topical Report Configurations/Scenario Terminology* (Gunter, 2000), the primary FEP *(2.2.14.07.00)* was also assigned to this configuration class. The primary FEP *(2.2.14.07.00)* involves a dryout (evaporation exceeds infiltration) that produces a fissile salt in the perched water basin, which is a different process than the precipitation of the fissile material in the perched water above TSbv of scenario configuration class FF-1c. Perhaps the far-field scenario in the Criticality Topical Report should be expanded to include the fissile salt formation.

Configuration class FF-1a corresponds to the primary FEP *(2.2.14.06.00)*.

Configuration classes FF-2a, FF-2b, and FF-2c correspond to the primary FEP *(2.2.14.08.00)*.

**Table C-1. Summary of review results for the primary criticality features, events, and processes**

| Features, Events, and Processes # | FEP Name, Description and DOE's Screening Argument | Screening Status | TSPA Status of Resolution | Review Comments |
|---|---|---|---|---|
| 2.1.14.00.00 | *Nuclear criticality (in wastes and EBS)*<br>This category contains FEPs related to nuclear criticality in the waste and engineered barrier system.<br>*N/A see subentries* | Header, see subentries | NA | |
| 2.1.14.01.00 | *Criticality in waste and EBS*<br>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) 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). Within the waste and EBS, critical assemblies may form within the waste container (in-situ) or out of container (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 ISC-1 through ISC-6 (for in-situ) and in FEPs NFC-1 through NFC-5 (for out of container).<br>*Since Yucca Mtn is being designed to accept CSNF, DSNF, and DHLW there is a substantial inventory of enriched fissile isotopes. Formation of critical assemblies in container and out of container have been considered for Yucca Mtn. While the likelihood of further enrichment out of container to the minimum necessary to reach a critical assembly is small, a number of possible cases have been identified for analyses. Heat, radiation and change in inventory are calculated to be insignificant perturbations to the repository.*<br>*{Fresh criticality may result in different transport parameters. Heat may alter seepage, solubility, and chemical form. Long-term criticality may alter solubility and transport characteristics - J. Wilson, INEEL}*<br>*Far-field criticality is discussed under FEP 2.2.14a (critical assembly forms away from repository).* | I | S | The primary and secondary FEP names are not unique and should be more descriptive<br><br>Several secondary FEPs are missing screening statuses<br><br>The name of a secondary FEP does not contain the keyword “criticality” |
| 2.1.14.02.00 | *Criticality in-situ, nominal configuration, top breach*<br>The waste package (WP) internal structures and the waste form remain intact (nominal configuration). There is a breach near the top of the WP, which allows water to collect in the WP. Criticality then occurs in-situ.<br>*Commercial spent nuclear-fuel waste containers, have neutron absorbers added as amendments, such as boron, to reduce the likelihood that a critical assembly can form if the container is accidentally filled with water. This FEP has no stated mechanism to remove or separate the neutron absorber. Therefore, this process seems unlikely. Processes described in FEPs ISC-1 through ISC-6 are considered more probable. Whether it is physically possible to actually fill the container before heating from fissions drives up the temperature is also an open question. {Criticality evaluation will probably show that intact basket and rods will not go critical - J. Wilson, INEEL}* | E | U | Insufficient information for exclusion. The results of criticality evaluations should be included.<br><br>This primary FEP is excluded but contains an “included” secondary FEP (2.1.14.02.02). |

Table C-1. Summary of review results for the primary criticality features, events, and processes (cont'd)

| Features, Events, and Processes # | FEP Name, Description and DOE's Screening Argument | Screening Status | TSPA Status of Resolution | Review Comments |
|---|---|---|---|---|
| 2.1.14.03.00 | *Criticality in situ, WP internal structures degrade faster than waste form, top breach*<br>The waste package (WP) internal structures degrade, but not the waste form. There is a breach near the top of the WP, which allows standing water to collect in the WP. Significant amounts of the neutron absorber are flushed out the top of the WP and DSNF criticality occurs in-situ.<br>A screening argument must be developed for each category of DSNF and the proposed waste package configuration in which it is to be contained.<br>*The use of a more insoluble neutron absorber can ensure that the criticality limit (CL) is not exceeded.*<br>*{DSNF will use insoluble poison, but it may settle to bottom of WP}* | I | S | The names of two secondary FEPs do not contain the keyword “criticality” |
| 2.1.14.04.00 | *Criticality in-situ, WP internal structures degrade at same rate as waste form, top breach*<br>The waste package (WP) internal structures degrade at the same rate as the waste form. There is a breach near the top of the WP, which allows water to collect in the WP. Significant amounts of the neutron absorber are flushed out the top of the WP. A slurry with insufficient neutron absorbing material forms at the WP bottom and DSNF criticality occurs in-situ.<br>*A screening argument must be developed for each category of DSNF and the proposed waste package configuration in which it is to be contained.The use of a more insoluble neutron absorber can ensure that the criticality limit (CL) is not exceeded. {Until WP bottom is pierced, insoluble poison should mix with slurry}* | E | U | The FEP should not be excluded until appropriate screening arguments are developed.<br><br>This primary FEP is excluded but contains two “included” secondary FEPs (2.1.14.04.01 and 2.1.14.04.02)<br><br>The name of a secondary FEP does not contain the keyword “criticality” |
| 2.1.14.05.00 | *Criticality in situ, WP internal structures degrade slower than waste form, top breach*<br>The waste package (WP) internal structures degrade slower than waste form. There is a breach near the top of the WP, which allows water to collect in the WP. The waste form degrades, separating from the neutron absorbers. A slurry forms at the WP bottom and DSNF criticality occurs in-situ.<br>*Since the basket is mostly intact, the waste form will have limited ability to be transported away from the neutron absorbing material.*<br>*Because the neutron absorbing material remains in place, the waste form (and its fissile material) has only limited opportunity to relocate within the WP.*<br>*{Criticality evaluation needed to determine if fissile material slurry at bottom will go critical with intact/poison basket}* | I | S | The name of a secondary FEP does not contain the keyword “criticality” |

Table C-1. Summary of review results for the primary criticality features, events, and processes (cont'd)

| Features, Events, and Processes # | FEP Name, Description and DOE's Screening Argument | Screening Status | TSPA Status of Resolution | Review Comments |
|---|---|---|---|---|
| 2.1.14.06.00 | *Criticality in situ, waste form degrades in place and swells, top breach*<br>The waste package (WP) internal structures remain intact while the waste form degrades. There is a breach near the top of the WP, which allows water to collect in the WP. The waste form degrades in place, but swells into a more reactive configuration, which may overwhelm the in-place neutron absorbing material. DSNF criticality occurs in-situ,<br>*Swelling of the fissile material within the internal structures, which remain relatively intact, could result in a more reactive geometry, particularly for highly enriched reactor fuel. A deterministic Criticality Evaluation may be able to dismiss this due to a small k-effective.*<br>*{Criticality evaluation may dismiss criticality with in-place fissile material and insoluble poison retained in oxide/clay}* | I | S | |
| 2.1.14.07.00 | *Criticality in situ, bottom breach allows flow through WP, fissile material collects at bottom of WP*<br>There is a breach at the bottom of the waste package (WP), which does not allow water to collect in the WP. Moderation is provided by water retained in clay or hydrated metal corrosion products accumulating in the bottom of the WP with the fissile material. Significant amounts of the neutron absorber are either flushed from the WP or remain distributed throughout the WP, while fissile material collects at bottom of the WP. DSNF criticality occurs in-situ.<br>*If the neutron absorbing material is flushed from the package criticality could occur. Or, if the neutron absorbing material remains intact while the fissile material migrates to a more reactive geometry, a criticality could occur. The use of a more insoluble neutron absorber can ensure that it will not be flushed from the WP. Also, by remaining intact the internal structure will limit the migration of the waste form.*<br>*{Must model criticality evaluation with insoluble poison to see if sufficient is retained in clay}* | I | S | |
| 2.1.14.08.00 | *Criticality in situ, bottom breach allows flow through WP, waste form degrades in place*<br>There is a breach at the bottom of the waste package (WP), which does not allow water to collect in the WP. 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. DSNF criticality occurs in-situ. | I | S | The names of three secondary FEPs do not contain the keyword "criticality" |

**Table C-1. Summary of review results for the primary criticality features, events, and processes (cont'd)**

| Features, Events, and Processes # | FEP Name, Description and DOE's Screening Argument | Screening Status | TSPA Status of Resolution | Review Comments |
|---|---|---|---|---|
| 2.1.14.09.00 | *Near-field criticality, fissile material deposited in near-field pond*<br>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.<br>*Because deterioration of the waste package is from the bottom, and thereby gradual, soluble poison would continually be flowing into the pond and need to be leached out prior to criticality. Because of the continual poisoning and gradual corrosion, this criticality would occur much later in time and possibly have lower consequences.*<br>*A similar scenario, intact fuel in pond due to top breach, appears to be missing (unless its treatment under in-situ criticality scenarios is deemed sufficient).*<br>*{Even though WP corrodes from bottom, insoluble poison may separate from solution or settle beneath intact fissile material}*<br>*Formation of ponds is discussed under FEP 2.1.07ad (floor buckling/basin formation)* | I | S | Insufficient information is provided for the exclusion of two secondary FEPs (2.1.14.09.02 and 2.1.14.09.06).<br><br>The FEP name of 2.1.14.09.06 is mistakenly identical to 2.1.14.09.03.<br><br>The screening argument of the secondary FEP 2.1.14.09.03 is in disagreement with the TSPA disposition.<br><br>The names of two secondary FEPs do not contain the keyword “criticality” |
| 2.1.14.10.00 | *Near-field criticality, fissile solution flows into drift lowpoint*<br>Near-field criticality results when fissile material-bearing solution flows into a drift lowpoint. The poison has already been separated from the FM-bearing solution, either due to retention in intact OIC or prior removal by flowthrough leaching within the WP.<br>*The site of the criticality may collect FM from multiple waste package streams.*<br>*{If nearfield can retain FM solution, mountain-breathing may concentrate it}* | I | S | The names of three secondary FEPs do not contain the keyword “criticality” |
| 2.1.14.11.00 | *Near-field criticality, fissile solution is adsorbed or reduced in invert*<br>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.<br>*Reference 1 maintains that the natural precipitation of non fissile materials first will reduce the probability of criticality. However, the geometry of the precipitation zone (under the influence of gravity) allows zonal precipitation wherein the fissile and non fissile species may precipitate at different places within the zone. What is mechanism for water (or other moderator) to interact with critical configuration of fissile material ?*<br>*{New design has nonsorbing invert}* | E | U | Insufficient information for exclusion.If appropriate, a statement could be added that the new nonsorbing invert design renders this FEP unlikely.<br><br>The name of a secondary FEP does not contain the keyword “criticality” |

**Table C-1. Summary of review results for the primary criticality features, events, and processes (cont'd)**

| Features, Events, and Processes # | FEP Name, Description and DOE's Screening Argument | Screening Status | TSPA Status of Resolution | Review Comments |
|---|---|---|---|---|
| 2.1.14.12.00 | *Near-field criticality, filtered slurry or colloidal stream collects on invert surface*<br>Near-field criticality results when slurry or colloidal stream is filtered (i.e., neutron absorbers are removed) by WP corrosion products and collect on top of invert surface.<br>*Related FEPs are described under 3.2.01i (interaction with corrosion products) and 3.2.04y (colloid filtration)*<br>*{Nearfield sorption not required for assembly of critical mass}* | I | S | |
| 2.1.14.13.00 | *Near-field criticality associated with colloidal deposits*<br>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.<br>*The colloid-forming tendency of Pu may enhance its transportation capability, making it a significant contributor to the criticality potential, if the package failure occurs before the first 100,000 years.*<br>*Criticality due to colloid filtration in the invert is discussed under FEP NFC-5. Related FEPs are described under 3.2.04z (colloid transport and sorption) and 3.2.04y (colloid filtration).*<br>*{Exclude nearfield criticality because invert nonsorbing and evaluate whether new temperature design minimizes stress-relief cracks around drift}* | E | U | Insufficient information for exclusion. Screening argument seems to imply inclusion. |
| 2.1.14.14.00 | *Out-of-package criticality, fuel/magma mixture*<br>Interaction between fuel and magma dilutes fissile material, excludes water, and minimizes its return. For criticality to occur, neutron absorbers must also be removed.<br><br>*{Magma contains silica, which is a moderator, but much poorer than water. John Massari can run a simulation, given the composition of intruding magma, to calculate criticality for this case. Should be low probability.}* | E | U | Insufficient information for exclusion. No mention about results of criticality calculations for this geometry. |
| 2.2.14.00.00 | *Nuclear Criticality in Geosphere*<br>This category contains FEPs related to nuclear criticality in the geosphere.<br>*N/A see subentries* | Header, see subentries | NA | |

Table C-1. Summary of review results for the primary criticality features, events, and processes (cont'd)

| Features, Events, and Processes # | FEP Name, Description and DOE's Screening Argument | Screening Status | TSPA Status of Resolution | Review Comments |
|---|---|---|---|---|
| 2.2.14.01.00 | *Critical assembly forms away from repository*<br>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 FFC-1 through FFC-7.<br>*Multiple waste packages may combine, increasing fissile mass, even if the adjacent packages contain low-enriched fuel (criticality studies have shown that critical mass remains fairly constant when high-enriched fuel is diluted to 10% enrichment). This makes far-field criticality more credible.*<br>*The probability of far-field criticality must be reduced by the probability of significant holdup of fissile material within the waste package or in the near-field zone.*<br>*{Criticality evaluation will probably show that intact basket and rods will not go critical - J. Wilson, INEEL}*<br>*Criticality within the waste and EBS is discussed under FEP 2.1.14p.* | I | S | The description of the secondary FEP 2.2.14.01.04 is unclear.<br><br>Two secondary FEPs are missing screening statuses (2.2.14.01.03 and 2.2.14.01.04)<br><br>The names of two secondary FEPs are identical and should be more descriptive<br><br>The names of two secondary FEPs do not contain the keyword “criticality” |
| 2.2.14.02.00 | *Far-field criticality, precipitation in organic reducing zone in or near water table*<br>Fissile material is transported to an organic reducing zone and precipitates in a geometrically favorable configuration in or near water table. This process appears to assume minimal dilution in aquifer (e.g., particularly for transport to the Franklin Lake Playa). Therefore, either the probability of transport must be reduced due to the nonaquifer pathway to the Playa, or the probability of precipitation in a geometrically favorable configuration must be reduced due to prior dilution in the aquifer. Also, a higher mass of fissionable material can result in higher consequences.<br>*This process is given low probability due to unlikelihood of significant reducing zones at Yucca Mountain (Reference 2). {However, screening arguments for secondary entries suggest that "Organic reducing zones may be encountered within the alluvial aquifer or in the alluvial sediments at the assumed natural outfall of the tuff aquifer at Franklin Lake playa (Alkali Flats)."} The ranking of scenarios in Reference 1 is based upon importance, but the parameter driving the ranking is not indicated (e.g., probability, risk?). {Reducing zones unlikely}* | E | S | Excluded based on probability.<br><br>Insufficient information is provided for the exclusion of two secondary FEPs (2.1.14.02.01 and 2.1.14.02.02).<br><br>The names of two secondary FEPs are identical and should be more descriptive<br>do not contain the keyword “criticality” |

## Table C-1. Summary of review results for the primary criticality features, events, and processes (cont'd)

| Features, Events, and Processes # | FEP Name, Description and DOE's Screening Argument | Screening Status | TSPA Status of Resolution | Review Comments |
|---|---|---|---|---|
| 2.2.14.03.00 | *Far-field criticality, sorption on clay/zeolite in TSbv*<br>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<br>*{Clay/zeolite zones appear to be too diffuse}* | E | S | This is a primary-FEP that contains an "included" secondary-FEP (2.2.14.03.01).<br>The screening argument of the secondary FEP 2.2.14.03.01 is in disagreement with the TSPA disposition. |
| 2.2.14.04.00 | *Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ*<br>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. | ?? | U | The primary FEP is missing a screening status.<br><br>The screening argument of the secondary FEPs 2.2.14.04.01 and 2.2.14.04.02 are in disagreement with the TSPA disposition.<br><br>Screening of the secondary FEPs 2.2.14.04.02 contradicts the primary FEP argument. |
| 2.2.14.05.00 | *Far-field criticality, precipitation in perched water above TSbv*<br>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.<br>*Calculations will be done to determine if perched water could contain a chemistry capable of precipitating a fissionable amount of material.*<br>*{Evaluate perched water chemistry to determine if redox is possible}* | I | S | |
| 2.2.14.06.00 | *Far-field criticality, precipitation in fractures of TSw rock*<br>Fissile material is transported to Topopah Springs welded unit where it precipitates in a geometrically favorable configuration within the fractures.<br>*Reference 1 maintains that the natural precipitation of non fissile materials first will reduce the probability of criticality. However, the geometry of the precipitation zone (a linear crack) allows zonal precipitation wherein the fissile and non fissile species precipitate at different places along the fracture. {Redox unlikely}* | E | U | Unconvincing argument for exclusion |

**Table C-1. Summary of review results for the primary criticality features, events, and processes (cont'd)**

| Features, Events, and Processes # | FEP Name, Description and DOE's Screening Argument | Screening Status | TSPA Status of Resolution | Review Comments |
|---|---|---|---|---|
| 2.2.14.07.00 | *Far-field criticality, dryout produces fissile salt in a perched water basin*<br>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.<br>*This far-field criticality process may be more likely than others because it does not require a reduction mechanism. Reference 1 maintains that the natural precipitation of non fissile materials first will reduce the probability of criticality. However, the geometry of the precipitation zone (a perched water zone in the far-field) allows zonal precipitation wherein the non fissile species precipitates before the solution reaches the perched zone.*<br>*{Evaluate chromograph separation or evap due to mountain breathing (expand FEP to include cracks in farfield)}* | I | S | |
| 2.2.14.08.00 | *Far-field criticality associated with colloidal deposits*<br>Far-field criticality could result from colloids deposited in clays/zeolites in TSbv or deposited in perched water above the relatively impermeable TSbv.<br>*The colloid-forming tendency of Pu may enhance its transportation capability, making it a significant contributor to the criticality potential, if the package failure occurs before the first 100,000 years.*<br>*Related FEPs are described under 2.2.08an (colloidal transport in geosphere), FFC-2, and FFC-4*<br>*{Evaluate whether new temperature design minimizes far-field stress-relief cracks around drift}* | ? | U | The primary FEP is missing a screening status. |

In the screening status column
I = Include
E = Exclude

In the TSPA status column
S = Satisfactory
U = Unsatisfactory
TBD = To be determined
NA = Not applicable

**REFERENCES**

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# APPENDIX D:

# SUMMARY OF REVIEW RESULTS FOR THE BIOSPHERE FEATURES, EVENTS, AND PROCESSES

This appendix presents a summary of review results for the primary biosphere-related features, events, and processes (FEPs). Table D-1 provides a justification for the resolution status reported in Table 5 of this IRSR (as pertaining to the primary biosphere FEPs reported in the Biosphere FEP AMR (CRWMS M&O, 2000)). Because the U.S. Department of Energy (DOE) screening status was obtained from an AMR rather than the preliminary FEPs database, this information is more up-to-date than results presented for criticality and "orphan" FEPs. Staff noted the frequent use of exclusion screening arguments based on criteria drawn from the NRC-proposed rulemaking. Staff noted an incongruity that assessments based on the criteria "present knowledge" do not imply limitations to "current conditions". For example, present knowledge of climate changes indicates the existence of climate cycles. Climate is predicted to change in the future rather than to remain identical to current conditions. Table D-2 lists biosphere FEPs considered irrelevant by DOE for inclusion in the initial list (of FEPs) prior to screening. Following the review, staff concluded the FEPs listed in Table D-2, if they were to occur (however, unlikely), could impact Dose1, Dose2, and/or Dose3 integrated subissues.

Table D-1.  Review of biosphere features, events, and processes in CRWMS M&O (2000)

| FEP Number | FEP Name | DOE Screening Status | NRC Issue Resolution Status | NRC Review Comment on FEP Screening Status |
|---|---|---|---|---|
| 1.2.07.01.00 | Erosion/denudation | E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions |
| 1.2.07.02.00 | Deposition | E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions |
| 1.3.01.00.00 | Climate change, global | I | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions |
| 1.3.04.00.00 | Periglacial effects | E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions |
| 1.3.05.00.00 | Glacial and ice sheet effects, local | E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions |
| 1.4.01.00.00 | Human influences on climate | E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions |
| 1.4.01.02.00 | Greenhouse gas effects | E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions |
| 1.4.01.03.00 | Acid rain | E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions |
| 1.4.01.04.00 | Ozone layer failure | E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions |

Table D-1. Review of biosphere features, events, and processes in CRWMS M&O (2000) (cont'd)

| FEP Number | FEP Name | DOE Screening Status | NRC Issue Resolution Status | NRC Review Comment on FEP Screening Status |
|---|---|---|---|---|
| 1.4.06.01.00 | Altered soil or surface water chemistry | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 1.4.07.01.00 | Water management activities | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 1.4.07.02.00 | Wells | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 1.4.08.00.00 | Social and institutional developments | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 1.4.09.00.00 | Technological developments | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 1.5.02.00.00 | Species evolution | E | TBD | Regulatory basis for exclusion pending final standards |
| 2.2.07.03.00 | Capillary rise | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 2.3.02.01.00 | Soil type | I/E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions; dual status |
| 2.3.02.02.00 | Radionuclide accumulation in soils | I/E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 2.3.02.03.00 | Soil and sediment transport | I/E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions; dual status |
| 2.3.04.01.00 | Surface water transport and mixing | E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; cited Figure 2-2 shows evidence of temporary surface water; misinterpreted present knowledge as current conditions; dual status |

**Table D-1. Review of biosphere features, events, and processes in CRWMS M&O (2000) (cont'd)**

| FEP Number | FEP Name | DOE Screening Status | NRC Issue Resolution Status | NRC Review Comment on FEP Screening Status |
|---|---|---|---|---|
| 2.3.06.00.00 | Marine features | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 2.3.09.01.00 | Animal burrowing/intrusion | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 2.3.11.01.00 | Precipitation | I/E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions;dual status |
| 2.3.11.02.00 | Surface runoff and flooding | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 2.3.13.01.00 | Biosphere characteristics | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 2.3.13.02.00 | Biosphere transport | I/E | U | Regulatory basis for exclusion pending final 10 CFR Part 63; misinterpreted present knowledge as current conditions; dual status |
| 2.4.01.00.00 | Human characteristics (physiology, metabolism) | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 2.4.03.00.00 | Diet and fluid intake | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; consequence argument ok; dual status |
| 2.4.04.01.00 | Human lifestyle | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 2.4.07.00.00 | Dwellings | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 2.4.08.00.00 | Wild and natural land and water use | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 2.4.09.01.00 | Agricultural land use and irrigation | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 2.4.09.02.00 | Animal farms and fisheries | I | S | Rationale is acceptable |

Table D-1. Review of biosphere features, events, and processes in CRWMS M&O (2000) (cont'd)

| FEP Number | FEP Name | DOE Screening Status | NRC Issue Resolution Status | NRC Review Comment on FEP Screening Status |
|---|---|---|---|---|
| 2.4.10.00.00 | Urban and industrial land and water use | I | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 3.3.01.00.00 | Drinking water, foodstuffs and drugs, contaminant concentrations in | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 3.3.02.01.00 | Plant uptake | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 3.3.02.02.00 | Animal uptake | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 3.3.02.03.00 | Bioaccumulation | I | S | Rationale is acceptable |
| 3.3.03.01.00 | Contaminated nonfood products and exposure | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 3.3.04.01.00 | Ingestion | I/E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63; dual status |
| 3.3.04.02.00 | Inhalation | I | S | Rationale is acceptable |
| 3.3.04.03.00 | External exposure | I/E | S | Dual status |
| 3.3.05.01.00 | Radiation doses | I | S | Dual status |
| 3.3.06.00.00 | Radiological toxicity /effects | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 3.3.06.02.00 | Sensitization to radiation | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 3.3.07.00.00 | Nonradiological toxicity/effects | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 3.3.08.00.00 | Radon and radon daughter exposure | E | S | Rationale is acceptable |

In the screening status column—I represents Include, E represents Exclude
In the TSPA status column—S represents Satisfactory, U represents Unsatisfactory, TBD represents To Be Determined, NA represents Not Applicable.

**Table D-2. Features, events, and processes that could impact biosphere that the U.S. Department of Energy considered not applicable**

| Primary FEP Number | FEP Description | DOE Screening Status | NRC Issue Resolution Status | NRC Comment on DOE Screening Status |
|---|---|---|---|---|
| 0.1.09.00.00 | Regulatory requirements and exclusions | I | S | Acceptable rationale |
| 1.1.05.00.00 | Records and markers, repository | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 1.2.04.01.00 | Igneous activity | I | TBD | |
| 1.2.04.07.00 | Ashfall | I (in VA) | TBD | |
| 1.3.07.01.00 | Drought/water table decline | E | U | Technical basis documentation not provided |
| 1.3.07.02.00 | Water table rise | I/E | TBD | |
| 1.4.01.01.00 | Climate modification increases recharge | E | TBD | Regulatory basis for exclusion pending final standards, and technical basis documentation not provided |
| 1.4.11.00.00 | Explosions and crashes (human activities) | E | TBD | Regulatory basis for exclusion pending final 10 CFR Part 63 |
| 1.5.01.01.00 | Meteorite impact | E | U | Technical basis implies additional text justification needed |
| 1.5.01.02.00 | Extraterrestrial events | E | U | Regulatory basis for exclusion pending final standards |
| 2.1.01.01.00 | Waste inventory | I | TBD | |
| 2.1.09.21.00 | Suspensions of particles larger than colloids | E | U | Technical basis documentation not provided |
| 2.1.13.03.00 | Mutation | E | U | No screening argument |
| 2.2.07.12.00 | Saturated groundwater flow | I | TBD | |
| 2.2.07.13.00 | Water-conducting features in the saturated zone | I | TBD | |
| 2.2.07.14.00 | Density effects on groundwater flow | E | U | Screening argument incomplete |
| 2.2.07.16.00 | Dilution of radionuclides in groundwater | I | TBD | |

Table D-2. Features, events, and processes that could impact biosphere that the U.S. Department of Energy considered not applicable (cont'd)

| Primary FEP Number | FEP Description | DOE Screening Status | NRC Issue Resolution Status | NRC Comment on DOE Screening Status |
|---|---|---|---|---|
| 2.2.07.17.00 | Diffusion in the saturated zone | I | TBD | |
| 2.2.08.01.00 | Groundwater chemistry/composition in UZ and SZ | I | TBD | |
| 2.2.08.06.00 | Complexation in geosphere | I | TBD | |
| 2.2.08.07.00 | Radionuclide solubility limits in the geosphere | E | U | Screening argument incomplete |
| 2.2.08.09.00 | Sorption in UZ and SZ | I | TBD | |
| 2.2.08.10.00 | Colloidal transport in geosphere | I | TBD | |
| 2.2.08.11.00 | Distribution and release of nuclides from the geosphere | I | TBD | |
| 2.2.12.00.00 | Undetected features (in geosphere) | E | U | Screening argument suggests status is "include" |
| 2.3.01.00.00 | Topography and morphology | I | TBD | |
| 2.3.04.01.00 | Surface water transport and mixing | I | U | |
| 2.3.11.03.00 | Infiltration and recharge (hydrologic and chemical effects) | I | TBD | |
| 2.3.11.04.00 | Groundwater discharge to surface | I/E | U | |
| 3.1.01.01.00 | Radioactive decay and ingrowth | I | TBD | |
| 3.2.07.01.00 | Isotopic dilution | E ? | U | Screening status contains questionmark |
| 3.2.10.00.00 | Atmospheric transport of contaminants | I/E | TBD | |

In the screening status column—I represents Include, and E represents Exclude.
In the TSPA status column—S represents Satisfactory, U represents Unsatisfactory, TBD represents To Be Determined, and NA represents Not Applicable.

## REFERENCE

CRWMS M&O, *Evaluation of the Applicability of Biosphere-Related Features, Events, and Processes (FEP)*, ANL–MGR–MD–000011 Revision 00, Las Vegas, NV, CRWMS M&O, 2000.

# APPENDIX E:

# SUMMARY OF REVIEW RESULTS FOR THE "ORPHAN" FEATURES, EVENTS, AND PROCESSES

This appendix presents a summary of staff review results for "orphan" features, events, and processes (FEPs). "Orphan" FEPs refer to FEPs that cannot be classified as specific to any particular key technical issue. Table E-1 provides a justification for the FEPs resolution for the primary "orphan" FEPs reported in Table 5 (see "TSPAI" column). The primary FEPs presented in this table are from the preliminary Yucca Mountain Project FEP Database (U.S. Department of Energy, 1999). No other information was available at the time of review for the evaluation of the U.S. Department of Energy (DOE) screening decision pertaining to these "orphan" FEPs. The U.S. Nuclear Regulatory Commission review comments and the status of resolution will be updated when further information (e.g., updated DOE database or a FEP AMR) becomes available.

Table E-1.  Review of "orphan" features, events, and processes in the U.S. Department of Energy's database

| Features, Events, and Processes Number | *Features, Events, and Processes Name* and notes on database entry | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| 0.1.02.00.00 | *Time scales of concern*<br>This category of FEPs describes the timescale of concern over which the disposal system presents a significant health or environmental hazard.<br>The timescale of concern for the Yucca Mountain TSPA is specified by regulation to be 10,000 years.<br><br>TSPA disposition: “TSPA analyses cover the 10,000 year period of time specified by regulatory requirements.”<br>AMRs listed: ASTROID | I | S | Consistent with regulatory requirements. |
| 0.1.03.00.00 | *Spatial domain of concern*<br>This category of FEPs describes the spatial domain of concern over which the disposal system presents a significant health or environmental hazard.<br>The spatial domain considered explicitly in TSPA modeling extends from the land surface down to the repository and laterally away from the repository to the location of the exposure point, which has been defined based on regulatory requirements.  Individual model domains are described in the documentation of each TSPA model.<br>The spatial domain considered in developing the technical basis for the TSPA modeling (for example, in FEP screening and conceptual model development) varies for different phenomena.  For example, considerations of the potential effects of global climate change address a global domain.  The regional groundwater flow model addresses a regional scale.<br><br>TSPA disposition: “Discussion will include both modeling and regulatory issues (20 km boundary).”<br>AMRs listed: ASTROID | I | S | Exposure point consistent with regulatory requirements. |

Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)

| Features, Events, and Processes Number | *Features, Events, and Processes Name* and notes on database entry | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| 0.1.09.00.00 | *Regulatory requirements and exclusions*<br>This category of FEPs describes regulatory requirements and guidance specific to the proposed Yucca Mountain repository.<br>Federal regulations applicable to the long-term performance of the disposal system are 40 CFR Part 197, 10 CFR Part 63, and 10 CFR Part 960. These regulatory requirements provide the framework within which the TSPA is conducted.<br><br>TSPA disposition: not specified; see screening argument.<br>AMRs listed: ASTROID | I | S | |

Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)

| Features, Events, and Processes Number | ***Features, Events, and Processes Name*** **and notes on database entry** | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| 0.1.10.00.00 | *Model and data issues*<br>This category of FEPs describes issues identified by other programs related to modeling of the disposal system.<br>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.<br>Alternative conceptual models for groundwater flow have been considered in the development of the Yucca Mountain TSPA models.<br>Yucca Mountain is modeled in 2 and 3 dimensions for thermo-mechanical and thermo-hydrologic studies, in 3 dimensions for flow and transport in the UZ, and in 1, 2, and 3 dimensions for flow and transport in SZ.<br>YMP distinguishes several kinds of uncertainties that receive somewhat different treatments. For example, conceptual model uncertainty is distinguished from uncertainty due to natural variability, and from measurement and extrapolation uncertainty. The Project recognizes and accounts for each type of uncertainty where appropriate and tries to comply with the requirement to provide the regulators with a basis for "reasonable confidence."<br>Parameter distributions used in the TSPA models take into account available information about the physical basis for correlations.<br><br>TSPA disposition: not specified - see screening argument<br>AMRs listed: ASTROID | I | S | |

**Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)**

| Features, Events, and Processes Number | *Features, Events, and Processes Name* and notes on database entry | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| 1.1.09.00.00 | *Schedule and planning*<br>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.<br>In general, the TSPA is based on an assumption that the repository will be constructed, operated, and closed according to the design schedule. Changes in the scheduling of activities during operations will require approval of the regulator, and are outside the scope of the TSPA.<br>TSPA disposition: "excluded on the basis of regulatory requirements"<br>AMRs listed: ASTROID | E | S | |
| 1.1.10.00.00 | *Administrative control, repository site*<br>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.<br>Issues related to control of the site during operations are outside the scope of the TSPA. Active control of the site will be maintained after closure as long as is practicable, as required by 40 CFR 197.14. Also as required by 40 CFR 197.14, control over the site shall not be assumed to have any effect on the TSPA for more than 100 years.<br>The effects of up to 100 years of active control are excluded from the TSPA on the basis of low consequence: controlling the site for 100 years will have no consequence on the natural processes that affect long-term performance. Possible effects of active controls on disruptive human activities are excluded from the TSPA by the specification in the regulation of the form of human intrusion to consider.<br>TSPA disposition: "excluded on the basis of low consequence (natural processes) and regulatory requirements (human disruption)"<br>AMRs listed: ASTROID | E | S | Satisfied pending clarification on the regulatory intent limiting human intrusion scenarios. |

**Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)**

| Features, Events, and Processes Number | ***Features, Events, and Processes Name*** **and notes on database entry** | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| 1.1.11.00.00 | *Monitoring of repository*<br>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.<br>Monitoring activities undertaken for operational safety are outside the scope of the long-term assessment. Monitoring activities undertaken either during or after operations to verify long-term performance are relevant to the TSPA, and will be conducted as required by regulations. As required by regulation, these monitoring activities will be conducted with techniques that do not affect the performance of the repository. The assumption for Yucca Mtn is that monitoring wells will be located at reasonable locations downgradient from the repository and assessments of exposure will be made for water removed from them. Monitoring wells thus do not represent such a short circuit, particularly for a repository located in the UZ.<br>Effects of monitoring activities are, therefore, excluded from the TSPA calculations on the basis of low consequence. Related FEPs are 1.1.01a (open site investigation boreholes) and 1.4.04m (abandoned and undetected boreholes).<br>TSPA disposition: “Excluded on the basis of low consequence”<br>AMRs listed: ASTROID, U7080<br>PMR listed: TSPA, UZ | E | S | |

Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)

| Features, Events, and Processes Number | ***Features, Events, and Processes Name* and notes on database entry** | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| 1.4.02.01.00 | *Deliberate human intrusion*<br>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.<br>Consistent with the regulatory requirements of 40 CFR 197, all FEPs involving willful disruption of the repository by future humans who are aware of its presence and the risks it poses have been excluded.<br>TSPA disposition: “Excluded on the basis of regulatory requirements.”<br>AMRs listed: ASTROID<br>PMR listed: TSPA | E | S | |
| 1.4.02.02.00 | *Inadvertent human intrusion*<br>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.<br>Consistent with regulatory requirements, inadvertent human intrusion has been included in the TSPA by estimating the consequences of the penetration of the repository by a drill hole. This scenario is specified in 40 CFR 197 and 10 CFR 63 as an appropriate surrogate for all forms of inadvertent human intrusion.<br>TSPA disposition: “Included in the TSPA modeling.”<br>AMRs listed: ASTROID<br>PMR listed: TSPA | I | S | |

Table E-1.  Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)

| Features, Events, and Processes Number | ***Features, Events, and Processes Name* and notes on database entry** | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| 1.4.04.00.00 | *Drilling activities (human intrusion)*<br>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.<br>Consistent with regulatory requirements, inadvertent human intrusion by drilling is the only form of human intrusion considered in the TSPA. It is considered without regard for the goal of the drilling activity.<br>TSPA disposition: “Included in the TSPA human intrusion scenario.”<br>AMRs listed: ASTROID<br>PMR listed: TSPA | I | S | |
| 1.4.04.01.00 | *Effects of drilling intrusion*<br>Drilling activities that intrude into the repository may create new release pathways to the 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.<br>Human actions will be dealt with according to the regulations, namely the consequences of one or more stylized modes of human intrusion will be examined. The stylized human intrusion scenarios include drilling which intercepts a waste container and subsequent transport of radionuclides downward to the SZ.<br>TSPA disposition: “Included in stylized calculations of human actions ”<br>AMRs listed: ASTROID<br>PMR listed: TSPA | I/E | S | Dual status screening |

Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)

| Features, Events, and Processes Number | *Features, Events, and Processes Name* and notes on database entry | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| 1.4.05.00.00<br><br>See special note on secondary FEPs (1.4.05.10 and others) | Mining and other underground activities (human intrusion)<br>Mining and other underground human activities (e.g., tunneling, underground construction, quarrying) could disrupt the disposal system.<br>Consistent with regulatory requirements, the only mechanism of intrusion explicitly considered in the TSPA is drilling.<br>TSPA disposition: "excluded on the basis of regulatory requirements"<br>AMRs listed: ASTROID<br>PMR listed: TSPA | E | S | Note on secondary FEPS:<br>While regulatory requirements restrict the consideration of direct intrusion to a drilling event, no limitations are prescribed related to the alteration of the geosphere. The summary exclusion of human activity (tunneling, etc.) should be revisited and based on solid arguments. |
| 1.4.08.00.00 | *Social and institutional developments*<br>This category contains FEPs related to social and institutional developments that could affect the long-term performance of the repository. The most likely is social and institutional development resulting in new *activities, communities or cities in the vicinity of Yucca Mtn.*<br>*Consistent with regulatory requirements (10 CFR 63.115 (a)), "Features, events, and processes that describe the reference biosphere shall be consistent with present knowledge of the conditions surrounding the Yucca Mountain site*<br>*TSPA disposition: "Excluded on the basis of regulatory requirements."*<br>*AMRs listed: F0000*<br>*PMR listed: Bio* | *E* | *S* | |

Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)

| Features, Events, and Processes Number | ***Features, Events, and Processes Name*** **and notes on database entry** | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| *1.4.09.00.00* | *Technological developments*<br>*Technological developments may affect the long-term performance of the repository. These include changes in the ability of man to intrude the site, and changes that might affect contaminant exposure and its health implications.*<br>*Consistent with regulatory requirements, future human technologies are assumed to be the same as those of the present.*<br>*TSPA disposition: "Excluded on the basis of regulatory requirements."*<br>*AMRs listed: F0000*<br>*PMR listed: Bio* | *E* | *S* | |
| *1.4.11.00.00* | *Explosions and crashes (human activities)*<br>*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.*<br>*Consistent with regulatory requirements, drilling intrusion is the only future human action considered in the TSPA. Related FEPs are discussed in 1.4.02a (deliberate human intrusion). See FEP 2.1.12aa (gas explosions) for a discussion of repository-induced explosions.*<br>*TSPA disposition: "Exclude on basis of regulatory requirements."*<br>*AMRs listed: ASTROID*<br>*PMR listed: TSPA* | *E* | *S* | |

Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)

| Features, Events, and Processes Number | ***Features, Events, and Processes Name* and notes on database entry** | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| *1.5.01.01.00* | *Meteorite Impact*<br>*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.*<br>*The probability of a meteorite hit sufficient to exhume waste or to produce a crater whose fractures reach the repository depth has been calculated using the analysis produced for WIPP, adjusted for the difference in depth, and the current data on astroblemes. The threat is well below the probability cutoff for events and processes to be considered. (Additional text from George Barr ?)*<br>*TSPA disposition: "Excluded on the basis of low probability."*<br>*AMRs listed: ASTROID*<br>*PMR listed: TSPA* | *E* | *U* | *Secondary FEP 1.5.01.01.02 states that the probability in England is 6*10E-9, which is not significantly below regulatory threshold. Provide a quantitative (possibly bounding) argument to support screening based on low probability.* |
| *1.5.01.02.00* | *Extraterrestrial events*<br>*Extraterrestrial events (e.g., supernova, solar flare, gamma-ray buster, alien life forms) may affect long-term performance of the disposal system.*<br>*The probability of an extraterrestrial event occurring that would seriously affect the geosphere in the repository region is very small. Related FEPs are discussed under 1.5.01a (meteorite impact).*<br>*TSPA disposition: "Extraterrestrial events are not considered."*<br>*AMRs listed: ASTROID*<br>*PMR listed: TSPA* | *E* | *U* | *Specifiy if screened based on low probability or low consequence, and provide a summary quantitative argument.* |

**Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)**

| Features, Events, and Processes Number | *Features, Events, and Processes Name* and notes on database entry | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| *1.5.03.01.00* | *Changes in the earth's magnetic field*<br>Changes in the earth's magnetic field could affect the long-term performance of the repository.<br>Changes in the earth's magnetic field are excluded from the TSPA on the basis of low consequence.<br>In any case, future climate changes from all natural causes have been included in the TSPA (see FEP 1.3.01 Climate Change).<br>TSPA disposition: "Excluded on the basis of low consequence "<br>AMRs listed: ASTROID<br>PMR listed: TSPA | E | S | |
| 2.1.14.14.00 | *Out-of-package criticality, fuel/magma mixture*<br>Interaction between fuel and magma dilutes fissile material, excludes water, and minimizes its return. For criticality to occur, neutron absorbers must also be removed.<br>{Magma contains silica, which is a moderator, but much poorer than water. John Massari can run a simulation, given the composition of intruding magma, to calculate criticality for this case. Should be low probability.}<br>TSPA disposition: Not specified<br>PMR listed: Crit | *E* | *U* | *Screening disposition should be supported by sufficient information.* |
| *2.2.06.05.00* | *Salt creep*<br>*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. [A lengthy discussion of deformation and creep follows] (WIPP).*<br>*There is no salt at and around Yucca Mt and no rocks which are sufficiently plastic to creep in a similar manner.*<br>*TSPA disposition: "Not considered"*<br>*AMRs listed: ADD1, C1000*<br>*PMR listed: Tec, ISM* | *E* | *S* | |

Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)

| Features, Events, and Processes Number | ***Features, Events, and Processes Name*** **and notes on database entry** | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| *2.3.06.00.00* | *Marine features*<br>*This category contains FEPs related to marine and coastal features and processes. Processes include erosion, sedimentation, deposition, sea-level change, and storms.*<br>*Because of the distance from the Yucca Mountain repository to the nearest ocean, all FEPs related to marine and coastal features have been excluded from the TSPA on the basis of low consequence.*<br>*TSPA disposition: “Excluded on the basis of low consequence.”*<br>*AMRs listed: F0000*<br>*PMR listed: Bio* | *E* | *S* | |
| *3.3.06.02.00* | *Sensitization to radiation*<br>*Human and other organisms may become sensitized to radiation exposure so that its effects are more severe.*<br>*Regulatory requirements for the Yucca Mountain repository establish limits on allowable radiation dose, rather than on the resulting human health effects.*<br>*TSPA disposition: “Ignored”*<br>*AMRs listed: F0000*<br>*PMR listed: Bio* | *E* | *S* | |

Table E-1. Review of "orphan" features, events and processes in the U.S. Department of Energy's database (cont'd)

| Features, Events, and Processes Number | *Features, Events, and Processes Name* and notes on database entry | DOE Screening Status | NRC Issue Resolution Status | Comments from This Review |
|---|---|---|---|---|
| *3.3.07.00.00* | *Non-radiological toxicity/effects*<br>*This category contains FEPs related to the estimation of human health effects resulting from the non-radiological toxicity of the waste.*<br>*Long-term regulatory standards are set by the EPA in terms of radiation dose. Human health risks have been considered by the EPA in formulating the dose limit, and speculation about specific health effects is outside the scope of the TSPA. Chemical carcinogens were not considered in developing the EPA radiation protection standards, and therefore can be considered implicitly to have been excluded from the TSPA*<br>*TSPA disposition: "Excluded on the basis of regulatory requirements."*<br>*AMRs listed: F0000*<br>*PMR listed: Bio* | *E* | *S* | |

*In the screening status column—I represents Include and E represents Exclude.*
*In the TSPA status column—S represents Satisfactory, U represents Unsatisfactory, TBD represents To Be Determined, and NA represents Not Applicable.*

## REFERENCE

U.S. Department of Energy, *Yucca Mountain Features, Events, and Processes Database*, Revision 00b, Preliminary Version, Washington, DC, U.S. Department of Energy, 1999.

# APPENDIX F:

# SUMMARY OF THE CONCEPTUAL APPROACHES IN TPA VERSION 4.0 CODE FOR THE INTEGRATED SUBISSUES

The Total-system Performance Assessment (TPA) code is the primary tool that U.S. Nuclear Regulatory Commission (NRC) staff is using to independently examine aspects of U.S. Department of Energy's (DOE's) performance assessments (PA). The TPA code was developed to evaluate the performance of a potential geologic repository at Yucca Mountain (YM) and represents NRC's abstraction of the YM system. Therefore, the structure of the TPA code provides insight into those areas that NRC staff consider most important for evaluating repository performance. A complete discussion of the approach and features of the TPA Version 4.0 code can be found in Mohanty, et al. (2000).

The TPA code incorporates phenomena within each of the three subsystems—engineered system, geosphere, and biosphere—used to focus evaluations of DOE's abstractions (see Figure 3). The components of the subsystems [engineered barriers, unsaturated zone (UZ) flow and transport, saturated zone (SZ) flow and transport, direct release and transport, and dose calculations] are all explicitly included within the TPA code. The Integrated Subissues (ISI)s are addressed at different levels of complexity. The extent to which interdependencies are incorporated within the TPA Version 4.0 code is also variable. Hereafter, the TPA Version 4.0 code is identified as TPA 4.0.

The following discussion of the TPA 4.0 calculations provides a description of the implemented conceptual model and places the ISIs within the context of the current model abstraction. In the description that follows, ISIs relevant to aspects of the total system performance assessment calculation are identified, and the conceptual model for that part of TPA 4.0 is presented. The reader should not infer that when an ISI is identified, that all relevant phenomena within that ISI are implemented in TPA 4.0. After an overview, descriptions of: infiltration and deep percolation, near-field environment, undisturbed failure of the waste package (WP), disturbed failure of the WP (also called disruptive failures), radionuclide transport (RT), and the exposure of a receptor group are provided. Each section is related to the three subsystems and identifies the relevant ISIs in that part of the abstraction. ISIs are presented in bold face.

<u>Overview</u>

The TPA code models the repository, the surrounding geology and the local biosphere using repository geometry information from the EDA-II. Water enters the groundwater pathway as infiltration at the surface of YM. This water is apportioned among the repository subareas. A portion of water enters the repository subarea and creates an environment where the WPs are susceptible to corrosion. WPs can fail from corrosion or mechanical failure (including disruptive events). After WP failure, the waste form is exposed to percolating water. Radionuclides (RN) can then be released from the waste form and into the groundwater. The contaminated groundwater will pass through the UZ and through the SZ before its eventual uptake through a well by a receptor group. In the event of extrusive igneous activity, the groundwater pathway is bypassed and RNs are transported through the air pathway. RNs within the biosphere are available for uptake by a receptor group. The receptor group may also be susceptible to direct exposure.

<u>Infiltration and Deep Percolation</u>

The transition from precipitation to deep percolation occurs at the interface between the biosphere and the geosphere (i.e., the biosphere includes the near-surface where evapotranspiration takes place affecting net percolation). **Climate and infiltration** correlates to the variability in the precipitation, heterogeneity in the near-surface and heterogeneity in the geosphere. This variability affects calculations related to the **flow paths in the UZ, engineered barrier degradation, RN release rates [and solubility limits]**, and the **quantity and chemistry of water contacting WPs and waste forms**. Spatial heterogeneity in hydrologic properties also influences the spatial and temporal distribution of flow. Although the **climate and infiltration** are affected by characteristics in both the biosphere and the geosphere, it occurs in the geosphere and is evaluated accordingly.

The mean annual infiltration (MAI) is modified by time histories of mean annual precipitation and mean annual temperature. It is assumed that there is no lateral diversion between the ground surface and the water table and the flow field is determined by infiltration. The MAI is calculated using estimates of the elevation, soil depth, soil hydraulic properties, bedrock properties and climatic variables. The flux percolating through each subarea incorporates the variability of each of these parameters for the surface overlying the subarea. For each subarea, the calculated flux is normalized to the MAI through the subarea under current conditions. The flux is then recalculated for climatic change using modified values for the mean annual precipitation and the mean annual temperature and the normalized flux through the subarea.

<u>Near-Field Environment</u>

The near-field environment includes the interface between the geosphere and the engineered system. Consequently, the phenomena within the near-field is influenced by the surrounding geology, the thermal loading from emplaced waste, and the engineered structures and materials. Attributes of the near-field environment influence **engineered barrier degradation, RN release rates [and solubility limits]**, and the transport of these RNs through the near-field. **Engineered barrier degradation** is a function of temperature, humidity, water chemistry and the thickness of the water film on the WP. The attributes of the near-field environment (e.g., temperature, relative humidity (RH) and chemistry of percolating water) may be influenced by the **flow paths in the UZ.** The **flow paths in the UZ** will also influence the **quantity and chemistry of the water contacting WPs and waste forms**.

Infiltrating water (from the ground surface to the repository) will experience changes in its chemical composition as it percolates. As the water contacts materials comprising the engineered barriers of the repository, its chemical composition will experience further evolution. The area surrounding the repository will experience changes arising from the thermal load introduced by the emplaced waste. The characteristics of the near-field environment and the percolating water will influence the performance of the WP and the eventual release of the RN inventory.

The repository-horizon average rock temperature is calculated assuming a conduction-only model. The time history of the temperature for each subarea is calculated to incorporate spatial variability of the temperature profiles determined from the EDA-II WP design, drift spacing, ventilation, and the drip shield. The WP surface temperature and the maximum spent nuclear fuel (SNF) temperature are calculated using a multimode (i.e., conduction, convection, and radiation) heat transfer model for the drift and the calculated temperature of the drift wall (i.e., the average temperature of the repository subarea). These calculations can accommodate the introduction of backfill. In addition, the WP surface temperature and the repository temperature are utilized to compute RH.

The pH and the chloride concentration of the water contacting the WPs is estimated using results calculated from a MULTIFLO (Lichtner, et al., 2000) simulation. MULTIFLO calculates pH and chloride concentration for water percolating through the matrix of the tuffaceous rock. The amount of water percolating through the drift is calculated based on the time-dependent water flux while temperature profiles are calculated from the conduction-only heat transfer model.

The amount of water percolating through the drifts will vary over time owing to thermohydrologic and climatic effects. The former dominates over the first several thousand years, and the latter becomes increasingly important over longer time scales. The user can select among three thermohydrologic models. The first model assumes episodic reflux associated with time-dependent perching. The second assumes that refluxing water can be sufficient to depress the boiling isotherm in fractures and reach the WP during times when the WP temperature exceeds the boiling point of water. The third incorporates a procedure for calculating the depth water penetrates below the boiling isotherm. Once the penetration distance is greater than the dry-out zone thickness above the drifts, reflux water flows onto the drip shield and eventually the WP. Only one thermohydrologic model is used during a given simulation. The reflux rate is assumed to be zero after 10,000 years.

Undisturbed Failure of the Waste Package

The failure of emplaced waste packages can be considered as occurring from juvenile failures, **engineered barrier degradation,** or mechanical failure. Although, WPs are part of the engineered system, the behavior of the WPs will be influenced by attributes of the engineered barriers, the influence of the geosphere, and interactions between the engineered system and the geosphere. As discussed above, **engineered barrier degradation** is a function of temperature, humidity, water chemistry, and the thickness of the water film on the WP; these attributes may be influenced by the **flow paths in the UZ.** Fracturing or buckling of parts of the WP also can result in the **mechanical disruption of engineered barriers**. The failure will allow water to contact the waste form [**quantity and chemistry of water contacting waste packages and waste forms**] and influences the **RN release rates [and solubility limits]**.

The WP can fail in one of four ways: WP fabrication and handling (initial or juvenile failure), corrosion (including weld corrosion), mechanical failure, or disruptive events (disruptive failures). Initial failures are normally considered to occur at the start of the simulation, but the time of initial failure may be set in the input file. Disruptive failures can occur at any time during the simulation where packages remain intact. Corrosion failure is considered to occur at the time at which the inner WP overpack is penetrated by corrosion. Once one WP fails by corrosion, all WPs in the subarea are treated as having failed. Mechanical failure is considered to occur through fracturing of the outer overpack as a result of thermal embrittlement arising from long-term exposure to temperatures above 150 °C.

The modeled WP includes two distinct layers: a 2-cm outer overpack consisting of Alloy C-22 and a 5 cm inner overpack consisting of stainless steel type 316L. This approach is consistent with DOE conceptual EDA-II designs for the repository.

Corrosion of the WP is strongly determined by the environmental conditions. The temperature (average repository and WP surface) and RH are used to determine the integrity of the drip shield and the extent of the water film on the surface of the WP. The amount of water dripping onto the WP is not addressed in the corrosion model. However, corrosion could proceed through dry oxidation, humid air corrosion, or aqueous corrosion, depending on the RH of the near field. The temperature and the chloride concentration in this water film determine the mode of corrosion (localized pitting versus generalized corrosion). Corrosion will occur as localized pitting when the corrosion potential is greater than the repassivation potential. The most conservative case, corrosion of welded surfaces, can be evaluated by assigning appropriate values to the input parameters.

Disturbed Failure of Waste Packages (Disruptive Failures)

Disruptive failures are a direct manifestation of the interactions between the geosphere and the engineered system. For example, the **mechanical disruption of engineered barriers** can arise from seismicity, faulting, or igneous activity. The failure of WPS will allow **[quantity and chemistry of] water to contact the waste form [and WPs]** and influences the **RN release rates [and solubility limits]**. The inventory of those WPs failed by extrusive igneous activity will be transported to the biosphere via the airborne pathway only (discussed below under RT) and consequently, these WPs are not affected by water seeping into the repository. The failure of WPs by other modes of mechanical failure from disruptive events (i.e., fault displacement, seismicity and intrusive igneous activity) will allow **[quantity and chemistry of] water to contact the waste form [and WPs]** and influences the **RN release rates [and solubility limits]**.

Faulting failures are assumed to occur from the displacement of yet unknown faults or new faults, because it is assumed that DOE will not emplace WPs within the setback distance from known and well-characterized faults. Attributes of the fault zone—including the probability and magnitude of fault slip—are considered to be similar to those of the Ghost Dance and Sundance faults. Fault displacement will fail all intact WPs within the fault zone when the fault displacement (either through a single event or by cumulative displacement due to fault creep) exceeds a preestablished threshold.

Seismic failures are assumed to occur when seismic events result in rock fall that introduces sufficient levels of stress or deformation in the WP. A full history of seismic events is calculated for the duration of the simulation using a seismic hazard curve. The weight of the rock falling onto the representative WPs is estimated from the results of a drift stability analysis using the computer code UDEC (Itasca Consulting Group, Inc., 1996) and joint spacing. Based on the acceleration of the rock associated with the seismic event, the vertical extent of the rockfall is determined from the ground acceleration and the joint spacing of the drift ceiling. This rock is then assumed to fall from the top of an unbackfilled drift to the WP ignoring any effects due to the presence of the drip shield. The effects of this impact force on WP deformation and stress within the WP are calculated for a range of different rock categories and seismic events. WP failure from the impact load occurs if the impact stress caused by a rock falling onto the WP induces a plastic strain at the point of impact exceeding two percent elongation.

Volcanic failures are assumed to occur when a volcanic center forms within the proposed repository area. Two types of WP failure may occur in TPA 4.0. The first type of failure is from an extrusive event, which intersects the repository and ejects SF in the WPs into the air and impacts other WPS through lateral intrusion. The second type of failure is from an intrusive event, which disrupts WPs, but does not directly release SF to the accessible environment. The number of WPs impacted by the volcanic event is input with a characteristic probability distribution function for the extrusive event and the intrusive event. All WPs affected by a volcanic event are assumed to fail for both extrusive and intrusive events. For the extrusive event, the entire contents of the WP are assumed to be incorporated into ash and transported to the surface for direct release.

Radionuclide Transport

A transport mechanism is required to move RNs from the repository to a receptor location. The primary pathways for RT at YM are the groundwater pathway and the air pathway. In the case of volcanic activity, waste is entrained in ash that erupts from the mountain. RNs are transported through the air **(airborne transport)**, and eventually is deposited on the ground surface where they are redistributed in the soil **(redistribution of radionuclides in soil)**. This may result in surface contamination at the location of the receptor group.

Contamination can also be transported by groundwater to the receptor group. This contaminated groundwater must travel through the invert, the UZ, and the SZ before reaching the receptor location. The amount of contamination transported through the UZ and SZ is affected by the number of failed WPs (**engineered barrier degradation** and **mechanical disruption of engineered barriers**) and the **RN release rates (and solubility limits)**. In the UZ, the amount of RNs transported is dependent on the **quantity and chemistry of water contacting WPS and waste forms** and the **RN release rates and solubility limits**. Transport of RNs in the UZ incorporates the **climate and infiltration, the flow paths in the UZ**, and the **RN transport in the UZ**; whereas, transport in the SZ is characterized by the **flow paths in the SZ** and the **RN transport in the SZ.** Contaminants transported through the groundwater may eventually enter the biosphere through the pumping of groundwater. The extent of pumping and the associated **dilution of RNs in groundwater** is a function of the **lifestyle of the critical group**.

At the time of WP failure, whether it be from corrosion, initial failure, mechanical failure, or disruptive events, it is assumed that one or more holes are formed in the WP. The waste is then no longer protected from water percolating through the drift and RN release from the WP is possible. Releases are modeled to occur only by advection through the remnants of the WP because diffusive transport was found to be negligible. Releases may originate from the fuel matrix or from RNs located in the gap between the fuel cladding and the fuel matrix. The amount of water entering the WP is apportioned from the time dependent focused water percolating through the repository horizon. Water will be able to flow out of the lowest hole in the WP. The amount of water that must enter the WP before the onset of advective release will, therefore, depend on the location of this lowest hole. Once determined, the height of the lowest hole is assumed to remain unchanged throughout the simulation period. Water will fill the WP until the capacity, which is a function of the location of the lowest hole in the WP, is reached and thereafter the amount of water entering the WP will equal the amount of water flowing out of the WP. The height of the water in the WP determines the fraction of fuel wetted and varies among WP failure modes (juvenile, corrosion, or mechanical) and subareas. This fraction of fuel wetted can be modified to represent the protection offered by intact cladding. One of two different conceptual models are used for evaluating releases from WPs in each failure type; they are referred to as the bathtub model and the flow-through model. The flow-through model is similar to the bathtub model, with the exception that the fraction of SNF involved in release is determined independently from the water level, and there is no accumulation of water in the WP. Water entering the WP is assumed to be released immediately.

Dissolution of the waste form considers near-field environmental variables such as temperature and the pH of the contacting water. The WP temperature, calculated assuming an intact (i.e., dry) WP, is used for waste dissolution calculations. Dissolution from the SNF matrix may be modeled in one of four ways: release in the absence of Ca and Si, release in the presence of Ca and Si, release based on the formation of secondary minerals, and a user-defined release rate. The WP temperature will change over time. A constant pH is maintained throughout the simulation (i.e., it does not reflect the evolution of the water after contact with the WP or the waste form) and is based on results from MULTIFLO calculations. Once leached from the SNF matrix, the amount of contamination released to the water depends on solubility limits and the extent to which the SNF is wetted. The extent of SNF wetting varies by subarea for initial, seismic, and corrosion failures, while the SNF wet fraction is the same across the repository for volcanic and faulting events. Concentrations within the water flowing out of the WP are determined assuming a stirred tank model within the WP.

The releases are computed for each failure type (initial, faulting, volcanic, seismic, and corrosion) and the results summed to provide a time history of the total release rate from the subarea for each RN. RNs flow from the WP into the UZ below the repository through the invert and backfill (if present). Water from the WP can either travel through the invert material or run off as surface drainage, depending on the flow rate and material properties of the invert. Modeling of RN travel through the invert assumes steady-state flow through the invert and constant and uniform invert material properties. The flow through the UZ is assumed to be vertical along streamtubes. One streamtube is assigned to each repository subarea. Flow will occur either through the matrix or the fractures. The occurrence of fracture flow is determined from hydrologic properties within given units and the magnitude of deep percolation. Matrix diffusion and sorption within fractures are processes that may limit or retard transport in the UZ; however, these processes are assumed negligible. Any switching between fracture and matrix flow is assumed to occur at hydrostratigraphic interfaces.

RNs within the SZ are considered to be transported along streamtubes that are 1D representations of the SZ flow. The dimensions of the streamtubes are based on 2D simulations by Winterle, et al. (2000) and terminate at the location of the receptor group. Three streamtubes are used for the transport within the SZ. For each subarea, the center of the UZ streamtube is used to determine, which one of the three SZ streamtubes is utilized in calculations for transporting contamination downgradient to the receptor group location. Matrix diffusion within fractures is considered in the SZ as part of the TPA 4.0. The location of the tuff/alluvium interface is provided as a sampled input parameter.

The RNs released through an extrusive volcanic event are dispersed and deposited with the volcanic ash. Attributes of the volcanic event are based on past events in the YMR. The attributes of the event and the wind velocity determine the areal distribution of the volcanic ash and SNF deposition. The model described in Suzuki (1983) has been modified to calculate the distribution of the released inventory within the biosphere. The time-dependent RN areal densities are calculated assuming leaching, erosion, and radioactive decay.

<u>Exposure of the Receptor Group</u>

The exposure of the receptor group represents the culmination of the PA and requires the input of earlier components. These earlier components will establish the temporal and spatial distribution of RNs at the receptor location. The arrival of RNs at the location of the receptor group is a direct output of the SZ flow and transport model, which requires an evaluation of the **flow paths in the SZ** and the **RN transport in the SZ**. The concentration of contaminants in the air and on the soil arises from the **volcanic disruption of WPs**, the **airborne transport of RNs** after a volcanic event (when other gaseous releases are neglected), and the **redistribution of RNs in soil**. The processes within the biosphere will then result in the redistribution, buildup due to irrigation, dilution, and uptake of RNs. These processes are influenced by the **lifestyle of the receptor group**. Exposure is also impacted by the **climate and infiltration** through climatic conditions that determine whether the biosphere is classified as the current biosphere or a pluvial biosphere and the **redistribution of RNs in soil**. The approach taken to evaluate the exposure of receptor groups in TPA 4.0 makes use of the GENTPA code, which is a modification to the GENII code (Napier, et al., 1988) and is described below. The receptor group may be exposed to contamination transported through the groundwater pathway or released through extrusive igneous activity. Two standard groups are assumed as potential receptor groups. The first group is comprised of age specific individuals located within 20 km of the repository that use contaminated groundwater only for drinking and are exposed to surface contamination through inhalation and direct exposure. The second group is comprised of age specific individuals located at least 20 km from the repository that use the contaminated water for drinking, residential use, and agricultural use; they are also exposed to surface contamination through ingestion, inhalation, and direct exposure. A set of DCFs are calculated using unit concentration-based total effective dose equivalents of the internal GENTPA results for exposure from drinking water and surface contamination assuming current biosphere and pluvial biosphere conditions. The inclusion of the GENTPA code in the TPA suite of auxiliary codes permits the specification of a stochastic biosphere, a stochastic receptor group, and the selection of a time period prior to exposure during which irrigation of the soil occurred. For the groundwater pathway, these DCFs are applied to the concentrations at the well head (i.e., after dilution from well pumping and accounting for the fraction of plume mass captured). Similarly, the DCFs for soil contamination reflect the dilution and exponentially decreasing mass loading of RNs from surface processes.

## REFERENCES


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